

# **FEAMAC/CARES**

## **Stochastic-Strength-Based Damage Simulation Tool for Ceramic Matrix Composites**

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United States Advanced Ceramics Association (USACA) 40<sup>th</sup>  
Annual Conference on Composites, Materials, and Structures

January 25-29, 2016, Radisson Resort at the Port,  
Cocoa Beach, Florida

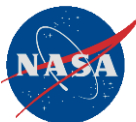
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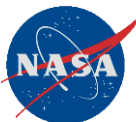
Glenn Research Center at Lewis Field

USACA 40<sup>th</sup> Annual Conference on Composites, Materials, and Structures



# Scope, Technical Challenge & Approach

- ❑ Predict the strength and service life of ceramic composite structures
- **Need to account for:**
  - Wide variability in the strength of individual components (probabilistic/stochastic strength)
  - How damage response changes with loading types (multiaxial loading, flexural loading, size effect)
  - How composite architecture effects strength/damage response
  - How strength degrades with time and fluctuating load
- **Approach → Combine two NASA developed codes:**
  - (MAC/GMC)** : composite micromechanics analysis &
  - (CARES/Life)** : probability of failure prediction of ceramic components coupled to commercial finite element analysis **(Abaqus)**



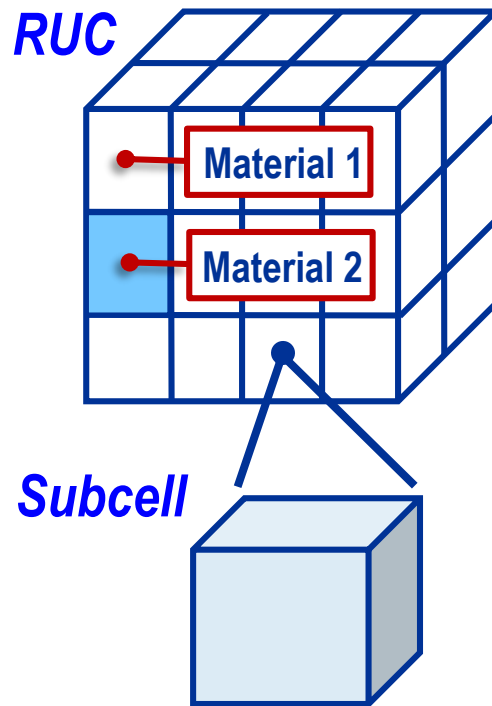
# Outline

1. Overview: Describe the MAC, CARES, & FEAMAC/CARES codes
  - ❖ Batdorf Unit Sphere stochastic-strength failure criteria
2. Applying CARES to the MAC code to simulate stochastic damage progression in a ceramic matrix composite (CMC)
  - ❖ **Cellular Automaton**: Encouraging failure of adjacent elements - mimics crack-like growth
3. Stress-strain response of a SiC-RBSN laminate (literature circa 1990)
  - ❖ Off-axis loading
  - ❖ Double-notched tensile specimen
4. *On-going work: Flexure-bar simulation – Is there a Weibull size effect ?*

# MAC/GMC Micromechanics Analysis Code

*Repeating Unit Cell (RUC)  
of composite material*

- ❖ RUC made of material subcells
- ❖ Multiscale capability



- **FEAMAC:** MAC/GMC embedded in FEA as constitutive material

# CARES/Life: Life Prediction Code For Advanced Ceramics

- Predicts the probability of failure of ceramic components under thermomechanical loading
- Combines Weibull & Weakest Link theory with concepts of linear elastic fracture mechanics (the *Batdorf Unit Sphere* model)
- CARES is a post-processor to FEA

## Component Reliability Analysis Capability:

- Transient loads and temperatures
- Fast-Fracture Rupture
- Time-dependent ( $da/dt$ ) crack growth
- Cycle-dependent ( $da/dn$ ) crack growth
- Multiaxial stress failure models (*PIA & Unit Sphere & Tsai-Wu & Tsai-Hill*)
- Proof test

# Approach for Life Prediction & Component Design of Composites

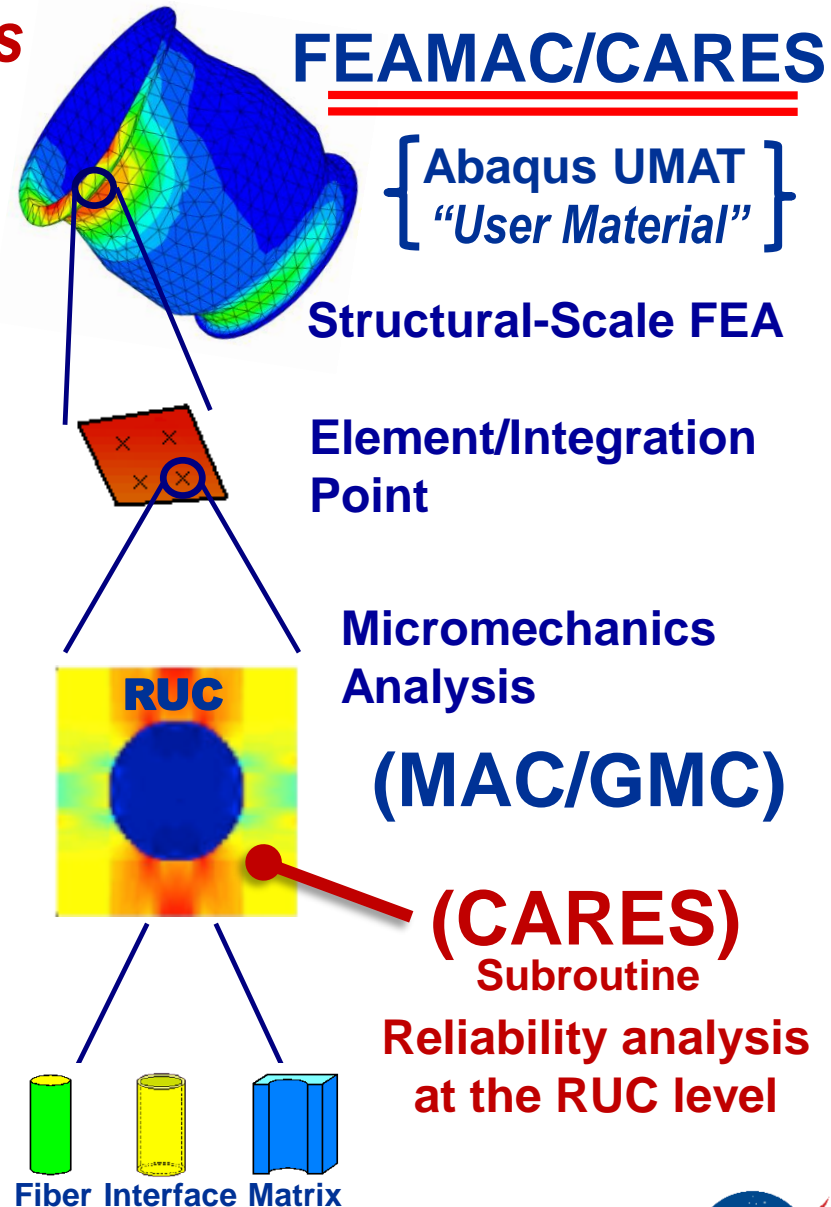
## ➤ *Combine CARES, MAC & FEA codes*

Move CARES from the macroscopic scale of the structure to the microscale of the individual RUC material constituents

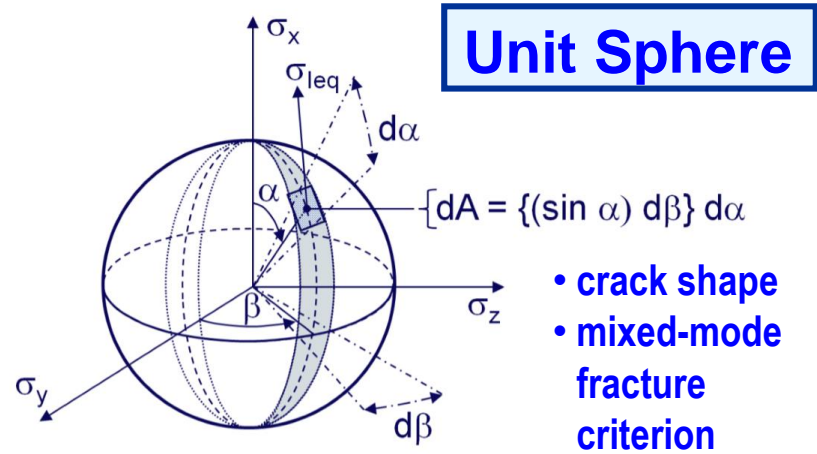
### ❖ FEAMAC/CARES Capability:

- Individual constituent and component level probability of failure tracked (for failure initiation)
- Individual & concurrent failure modes
- Laminate level analysis capability
- Progressive damage capability/simulation
- Subcells killed at random failure thresholds

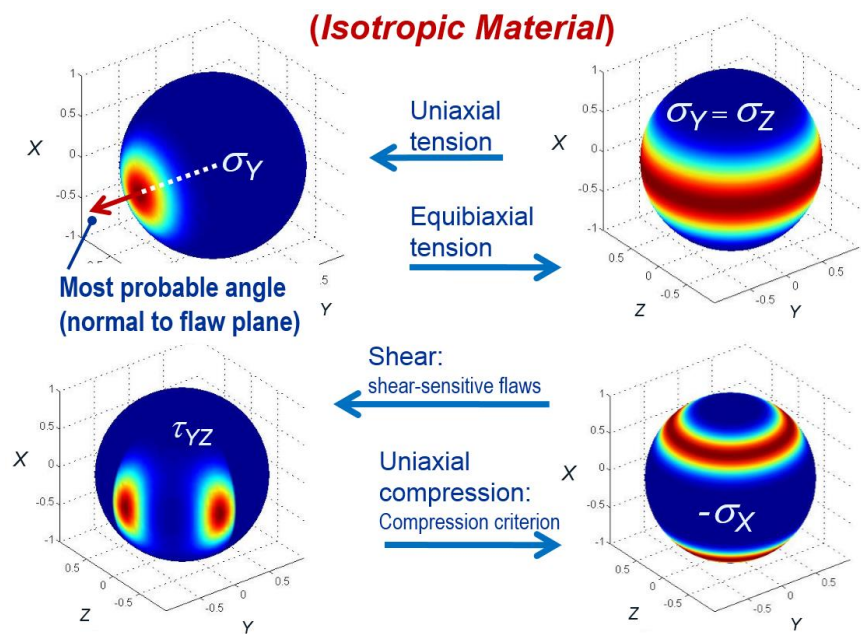
*Debonding/crack path physics at constituent level not explicitly included*



Fracture-mechanics-based failure criteria to predict probability of failure/damage of a material constituent over time



Unit Sphere Probability Density Distribution For Orientation Of Critical Flaws

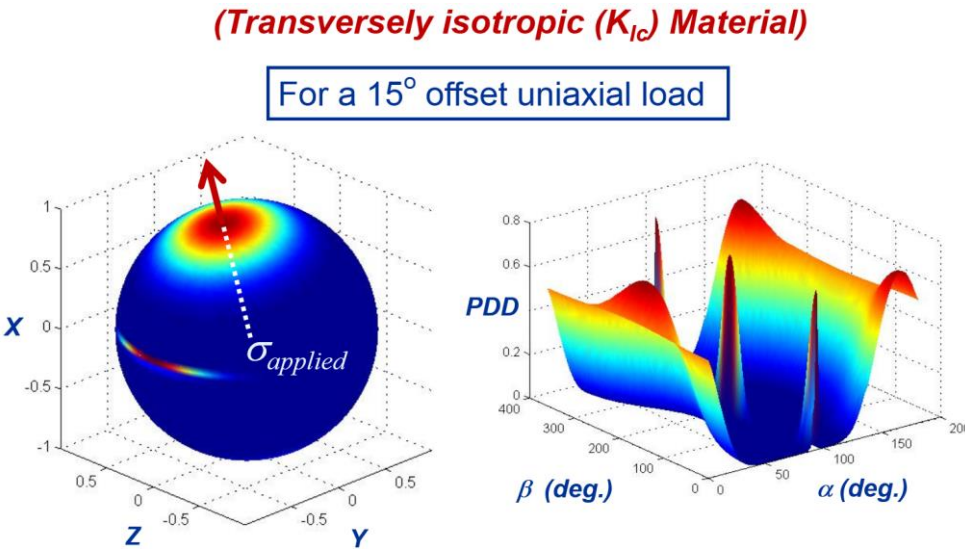


The unit sphere model is applied at the constituent level of the composite

Has been extended to anisotropy

- Two models for anisotropic strength response:
  - $K_{Ic}$  / Critical strength
  - Flaw orientation bias

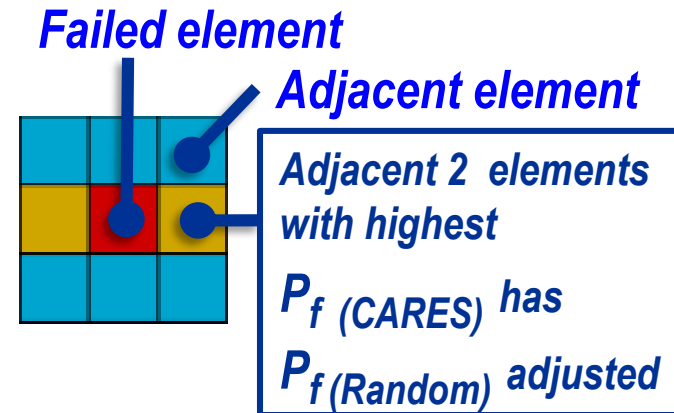
Unit Sphere Probability Density Distribution For Orientation Of Critical Flaws *for anisotropic material constituent*



# Random Element Failure vs: Neighbor Influenced Failure (Cellular Automaton Enhancement)

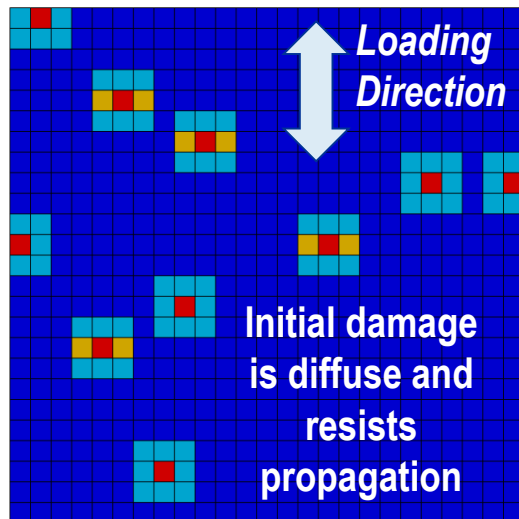
*Encourage more abrupt failure and “crack-like” damage growth patterns*

failure probability thresholds of elements  
adjacent to failed elements adjusted to promote  
a biased damage direction according to rules  
defined for a cellular automaton



*Random element failure*

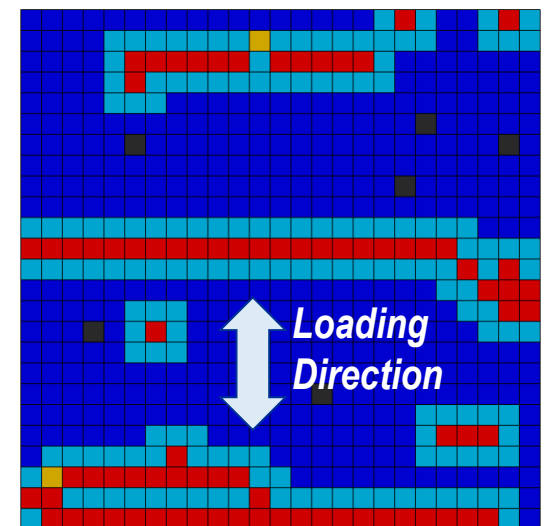
➤ *simulates stochastic toughening*



**Example: 0° Ply  
uniaxial ramp load  
25x25 FEA mesh  
of shell elements**

*With cellular automaton Rules*

➤ *“crack-like” growth patterns*





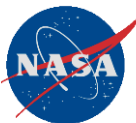
## Example: SiC/RBSN Laminated Composite in *On-Axis* & *Off-Axis* Loading

- Tested by Bhatt & Phillips (1990)

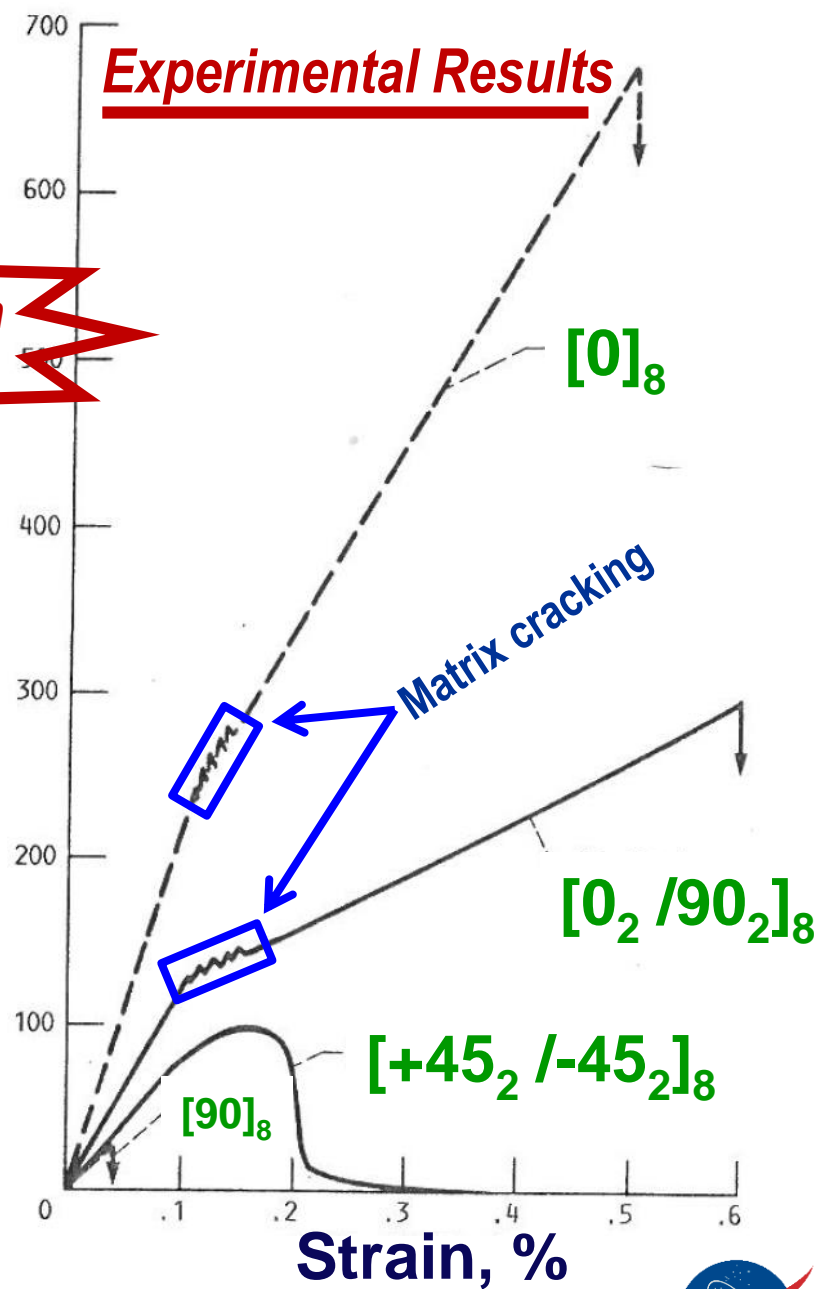
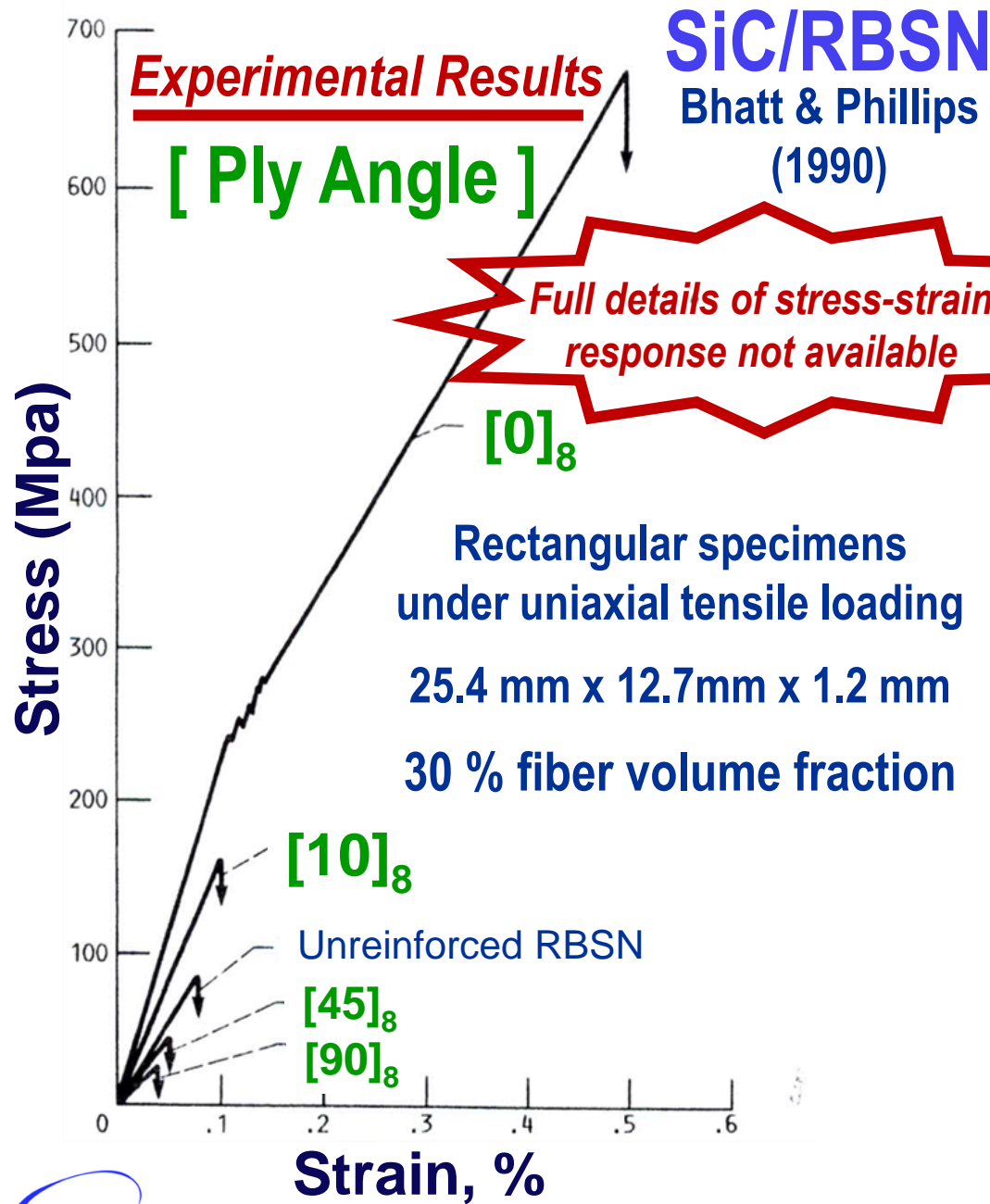
### ➤ displays key mechanisms/features for model material

- SCS-6 fiber/Reaction Bonded Silicon Nitride matrix composite examined in detail by NASA ➤ several papers published
- Laminated CMCs of interest to industry and less complex than woven composites
  - failure modes are not conflicted with complex fiber architecture
- [0] & [0/90] laminates display nonlinearity due to matrix failure, followed by fiber failure.
- Remaining ply orientations display sudden brittle failure.

Bhatt, R.T., and Phillips, R.E.: "Laminate Behavior for SiC Fiber-Reinforced Reaction-Bonded Silicon Nitride Matrix Composites." J. of Comp. Tech. & Res. V. 12, No. 1, Spring 1990, pp. 13-23.







# SiC/RBSN Example Procedure & Setup

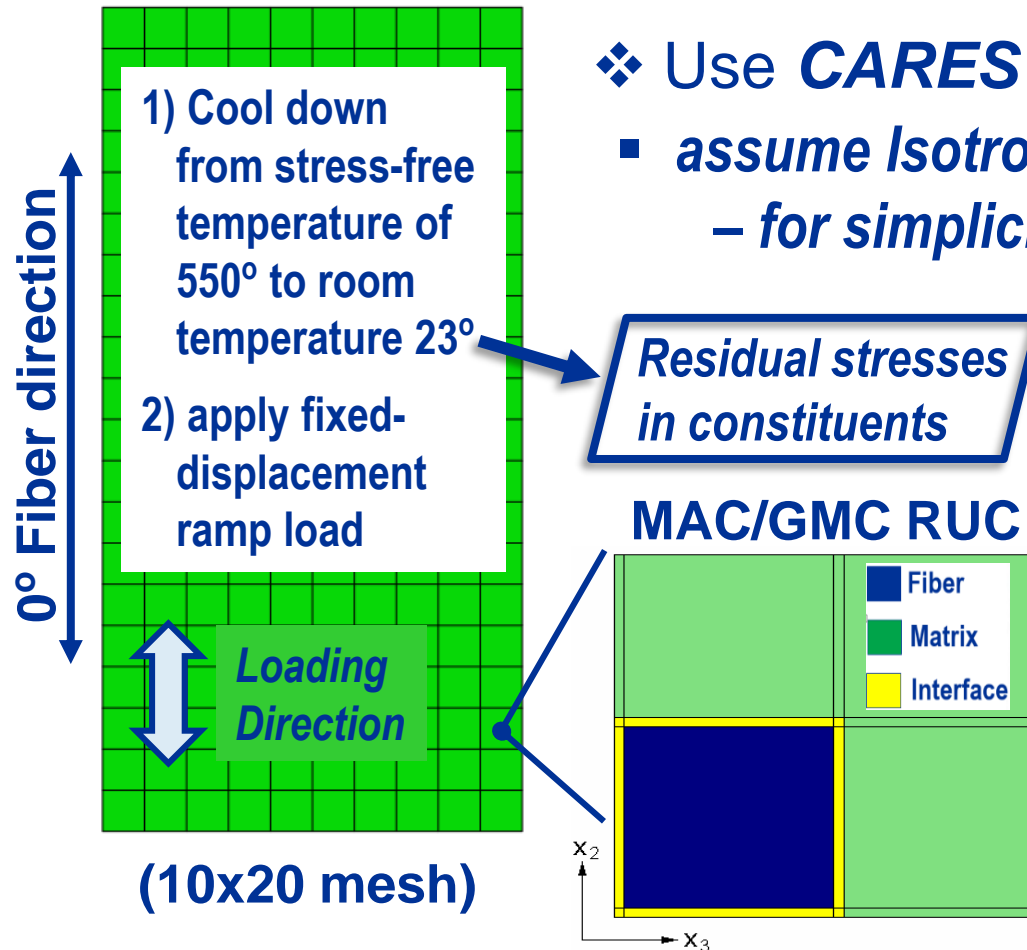
Abaqus FEA  
S4 Shell elements

Fixed-displacement ramp load

**Stochastic strength analysis:**

*(from individual trials / simulations / realizations)*

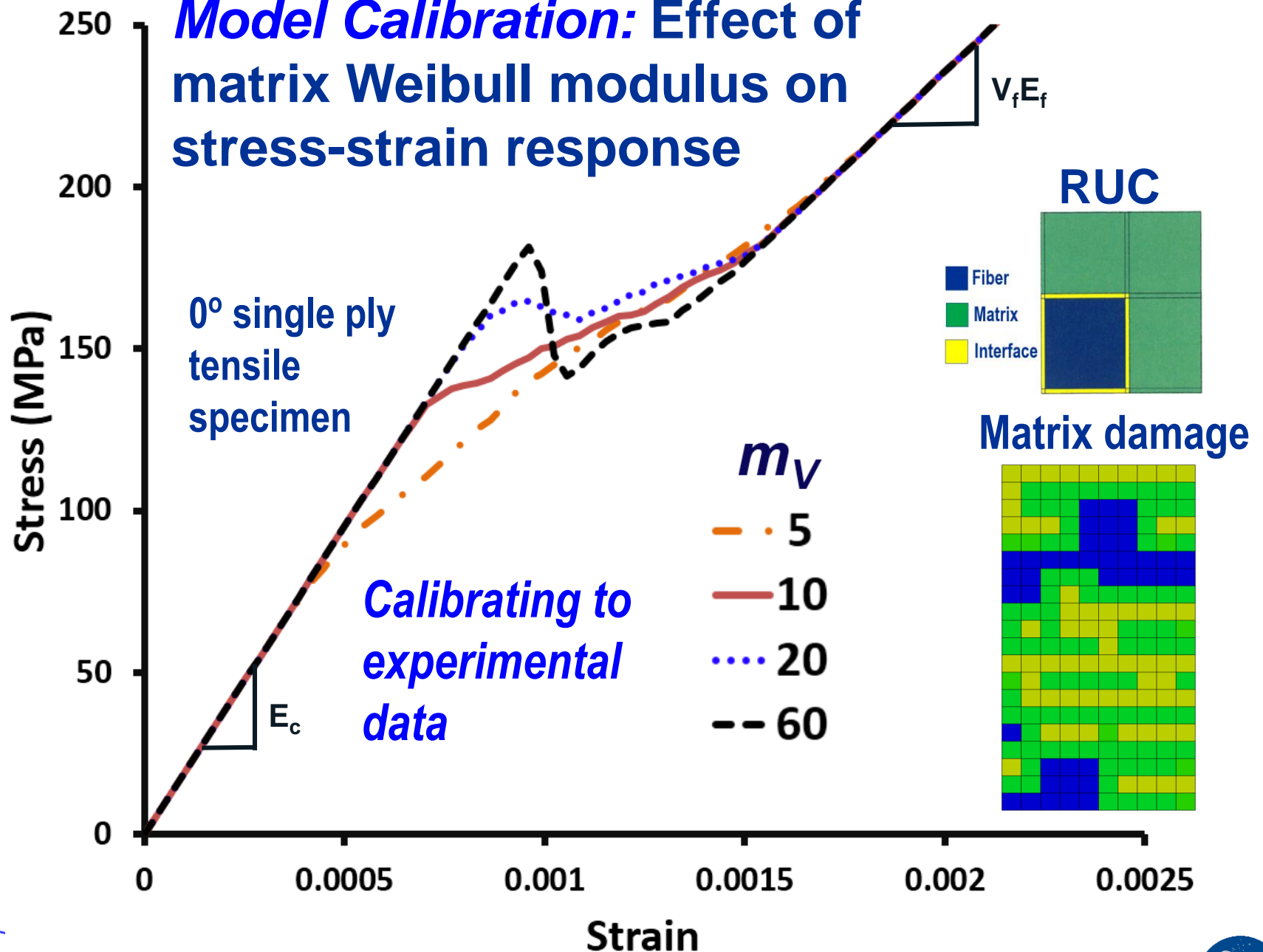
- ❖ Use **CARES Unit Sphere** failure criterion
  - assume *Isotropic material constituent strength*  
– for simplicity and initial testing



- a) **Calibration of model:**  
Correlate Weibull parameters and “stress-free” temperature to experimental results for 0° tensile specimen
- b) **Prediction of damage**  
response for off-axis plies and laminates

• Interface strength made large: *Encourage matrix to fail before interface*

# Model Calibration: Effect of matrix Weibull modulus on stress-strain response



# **Model Calibration: Constituent properties of SiC/RBSN with anisotropic thermal expansion coefficients**

Constituent	Modulus, GPa	Poisson ratio	Longitudinal coefficient of thermal expansion, $\alpha_L$ (m/m/°C)	Transverse coefficient of thermal expansion, $\alpha_T$ (m/m/°C)
Fiber	390	0.17	$4.1 \times 10^{-6}$	$1.84 \times 10^{-6}$
Matrix	110	0.22	$2.2 \times 10^{-6}$	$2.2 \times 10^{-6}$
Interface	1.8	0.22	$2.0 \times 10^{-6}$	$2.0 \times 10^{-6}$

## **Assumed Weibull Parameters:**

**Fiber**             $m_v = 20$              $\sigma_{oV} = 2875 \text{ Mpa} \bullet m^{3/20}$

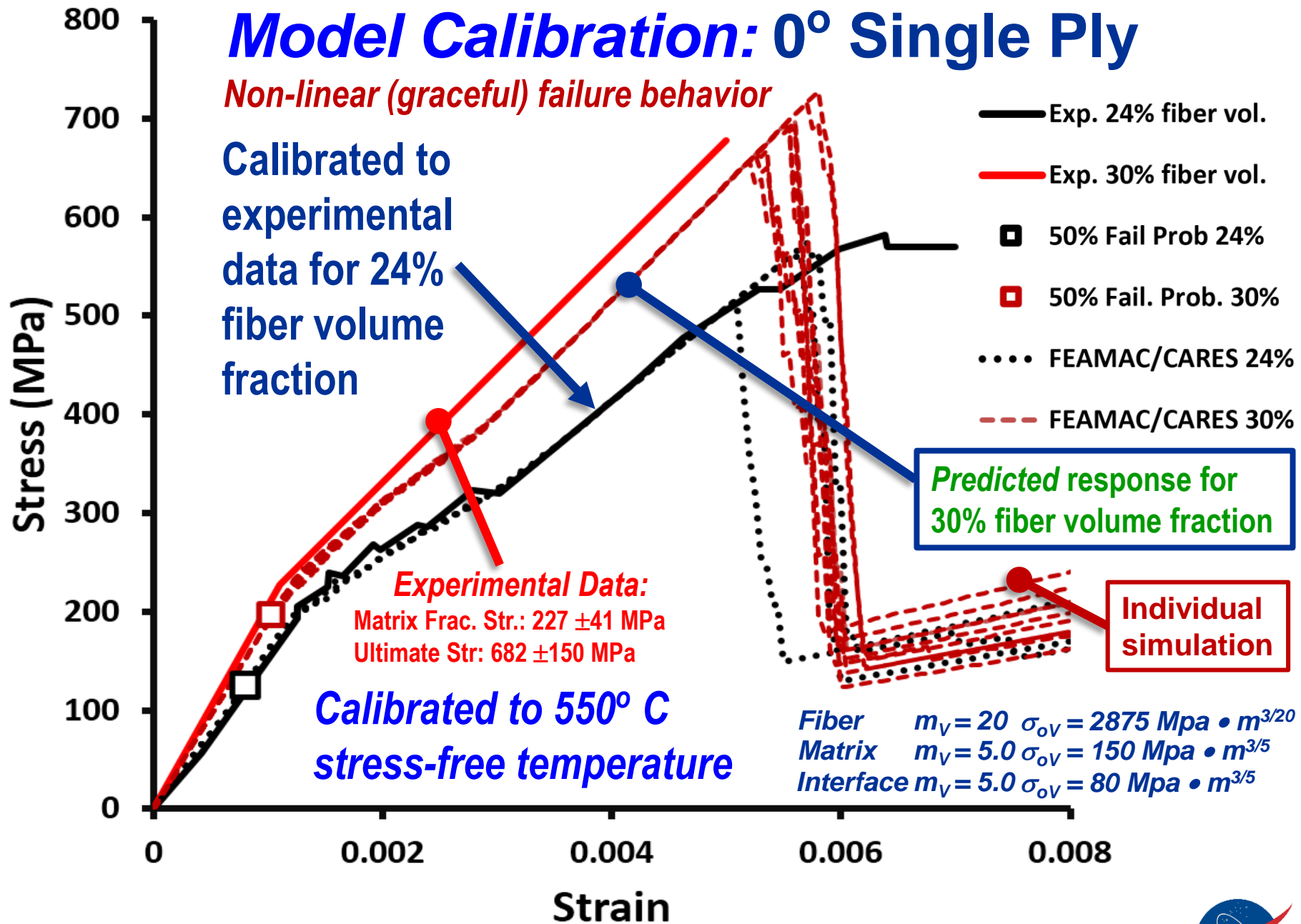
**Matrix**             $m_v = 5.0$              $\sigma_{oV} = 150 \text{ Mpa} \bullet m^{3/5}$

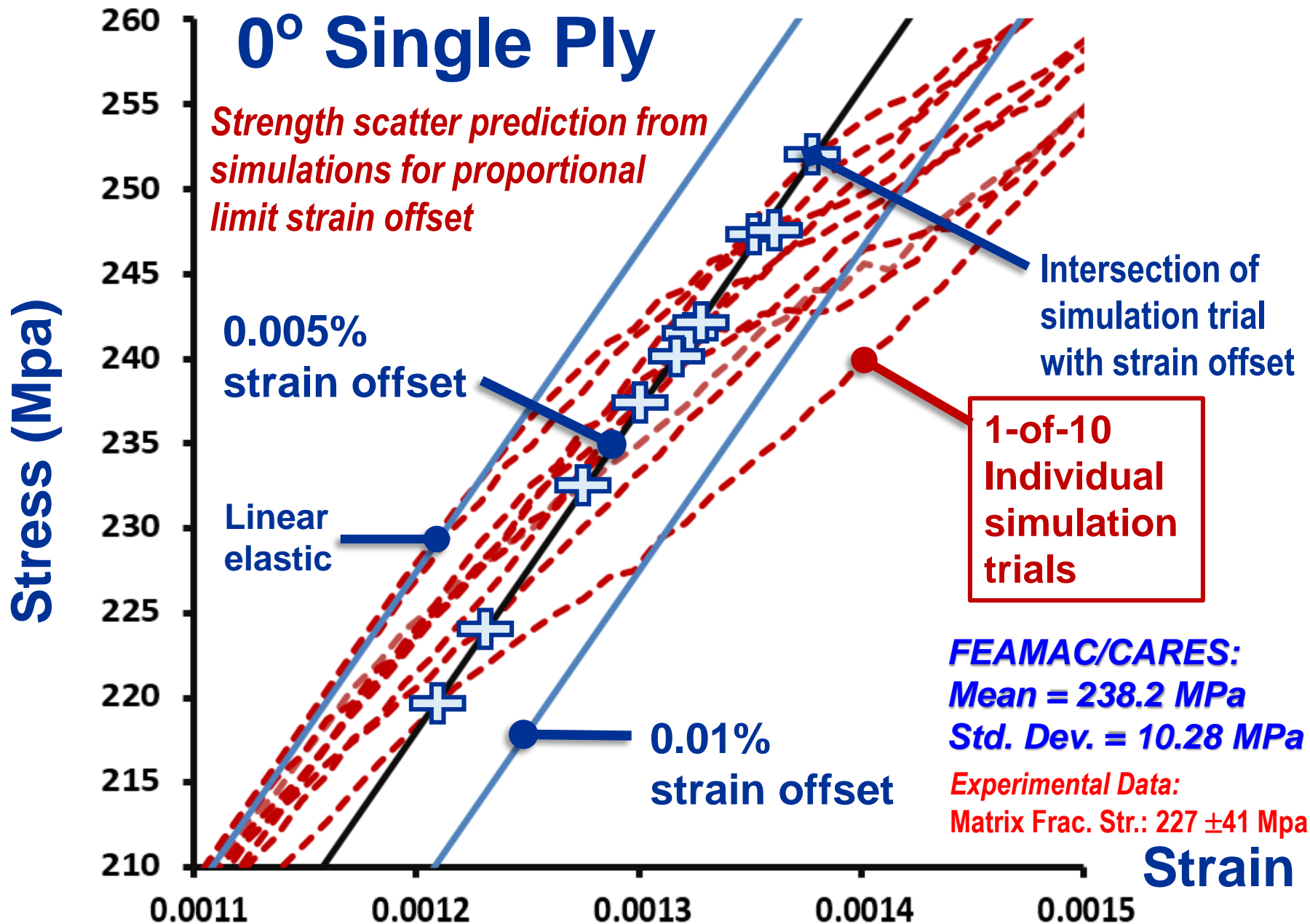
**Interface**             $m_v = 5.0$              $\sigma_{oV} = 80 \text{ Mpa} \bullet m^{3/5}$

# Model Calibration: 0° Single Ply

*Non-linear (graceful) failure behavior*

Calibrated to  
experimental  
data for 24%  
fiber volume  
fraction

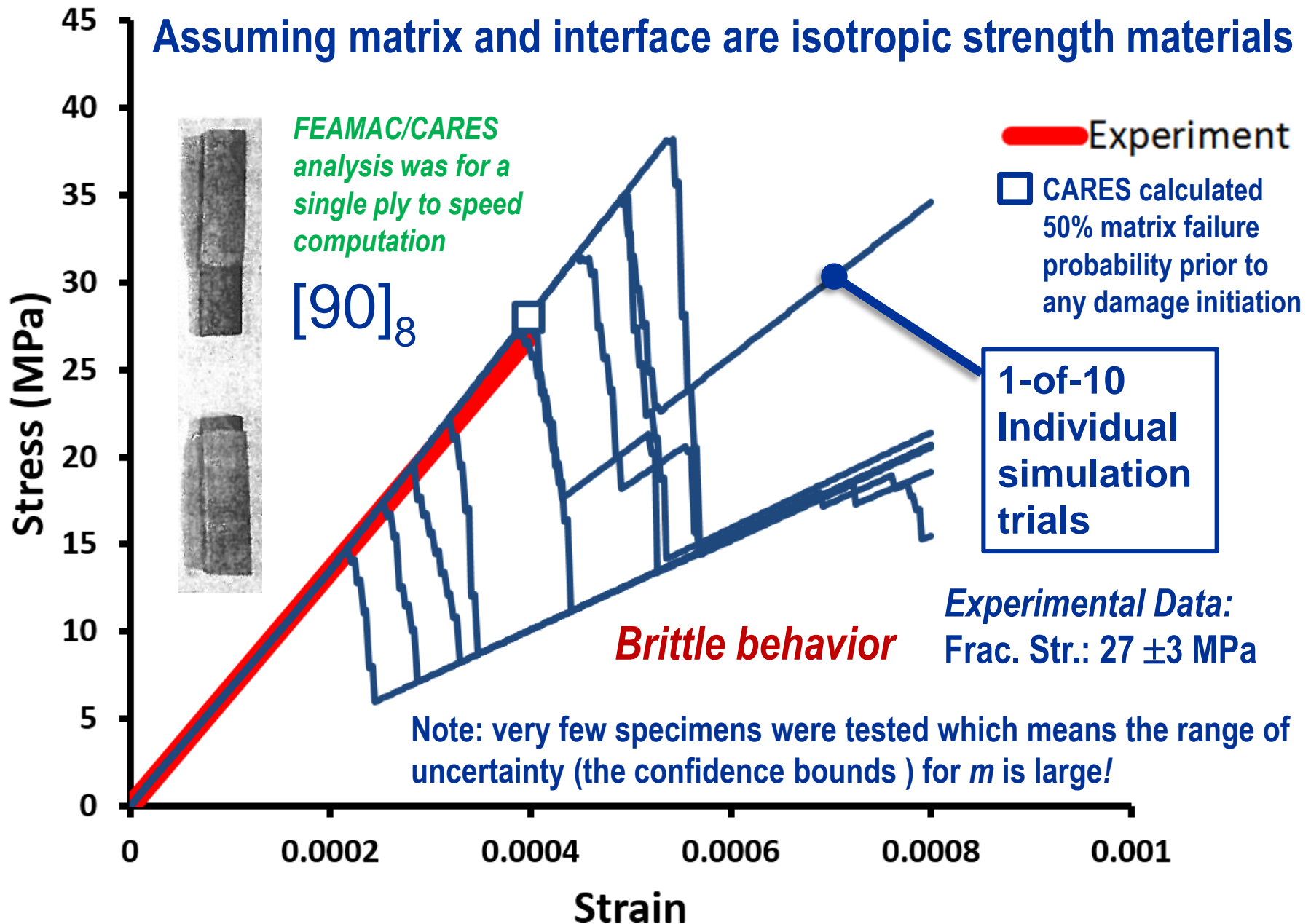




PLS is defined as the stress at 0.005% strain offset:

Kalluri, S; Calomino, A; and Brewer, D., "Computation of Variability in the Average Thermal and Mechanical Properties of a Melt-Infiltrated SiC/SiC Composite", High Temperature Ceramic Matrix Composites 5, M. Singh, R.J. Kearns, E. Lara-Curzio, R. Naslain, Eds, 2004, pp. 279-284

# Model Calibration & Prediction: Ten Trials for 90° Fiber Orientation



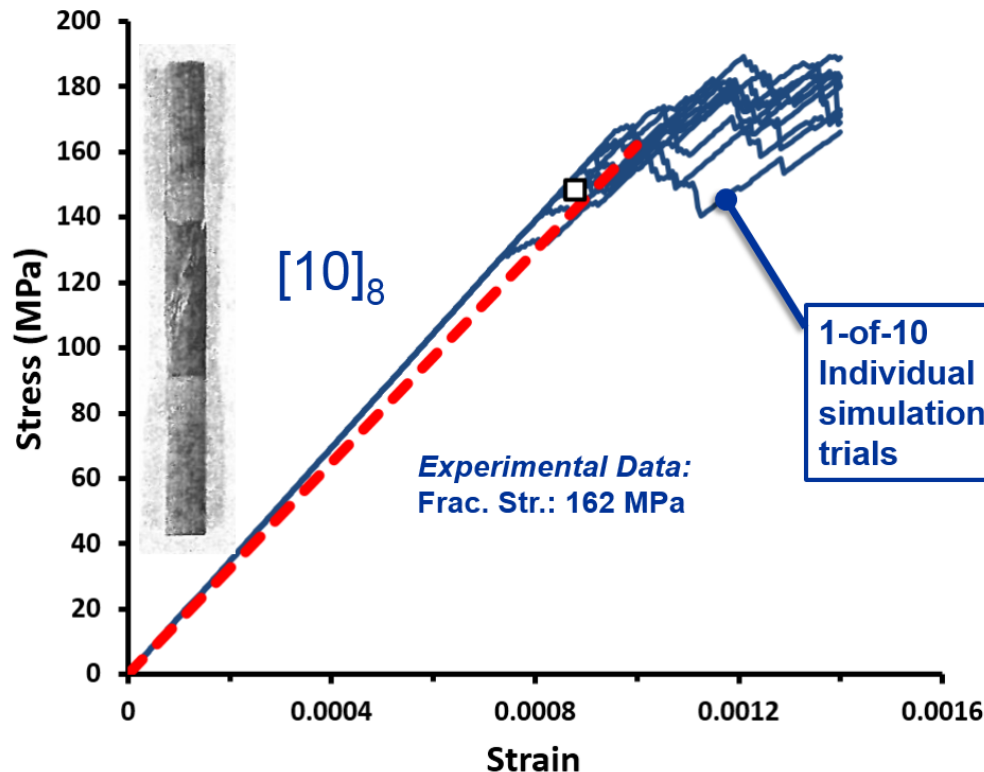


# Predictions for Ten Trials for 10° and 45° Fiber Orientations

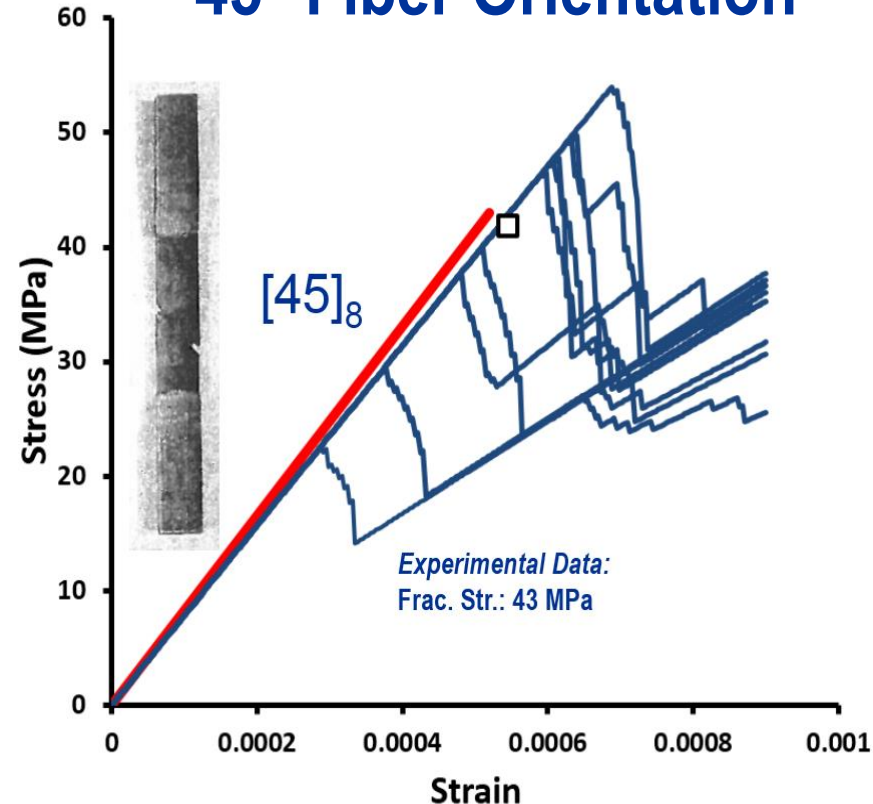
Assuming matrix and interface are isotropic strength materials

*FEAMAC/CARES analysis was for a single ply to speed computation*

## 10° Fiber Orientation



## 45° Fiber Orientation



Experiment

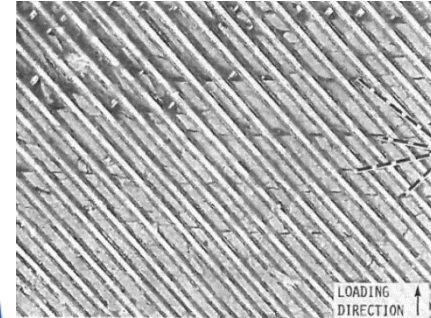
□ CARES calculated 50% matrix failure probability prior to any damage initiation

# Prediction for Ten Trials for $[+45_2/-45_2]_s$ Fiber Orientation

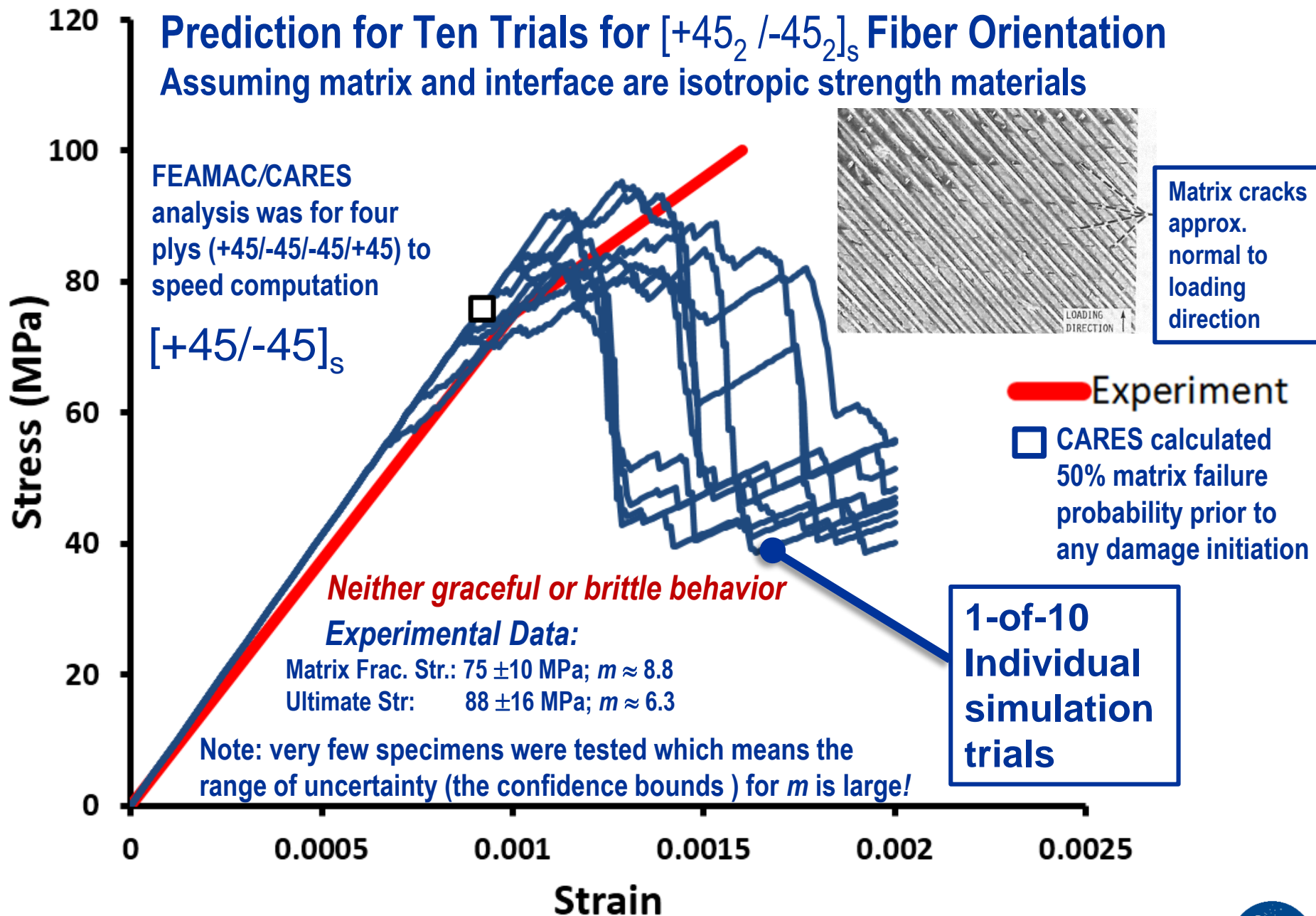
Assuming matrix and interface are isotropic strength materials

FEAMAC/CARES  
analysis was for four  
plys (+45/-45/-45/+45) to  
speed computation

$[+45/-45]_s$

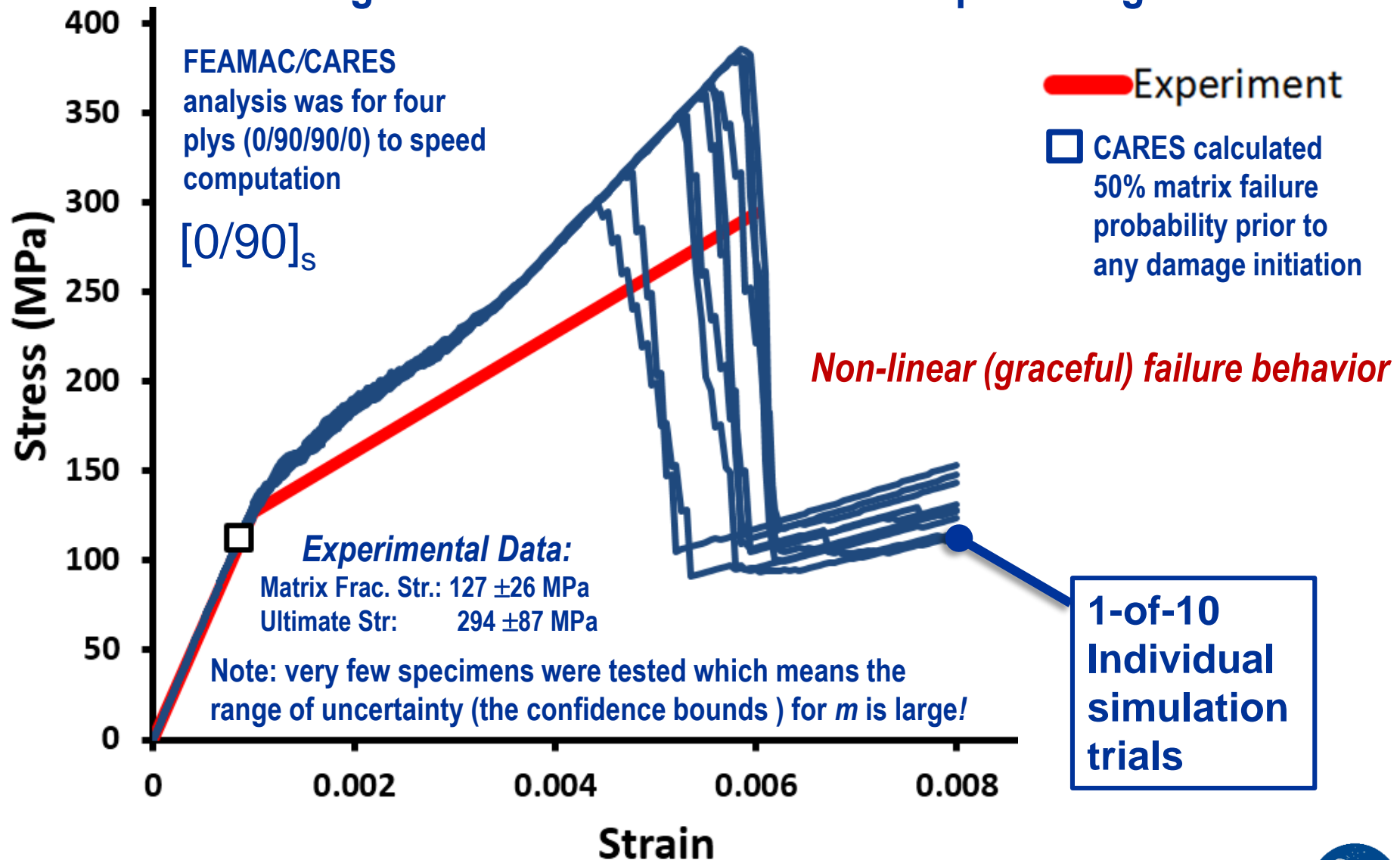


Matrix cracks  
approx.  
normal to  
loading  
direction



# Prediction for Ten Trials for $[0/90]_s$ Fiber Orientation

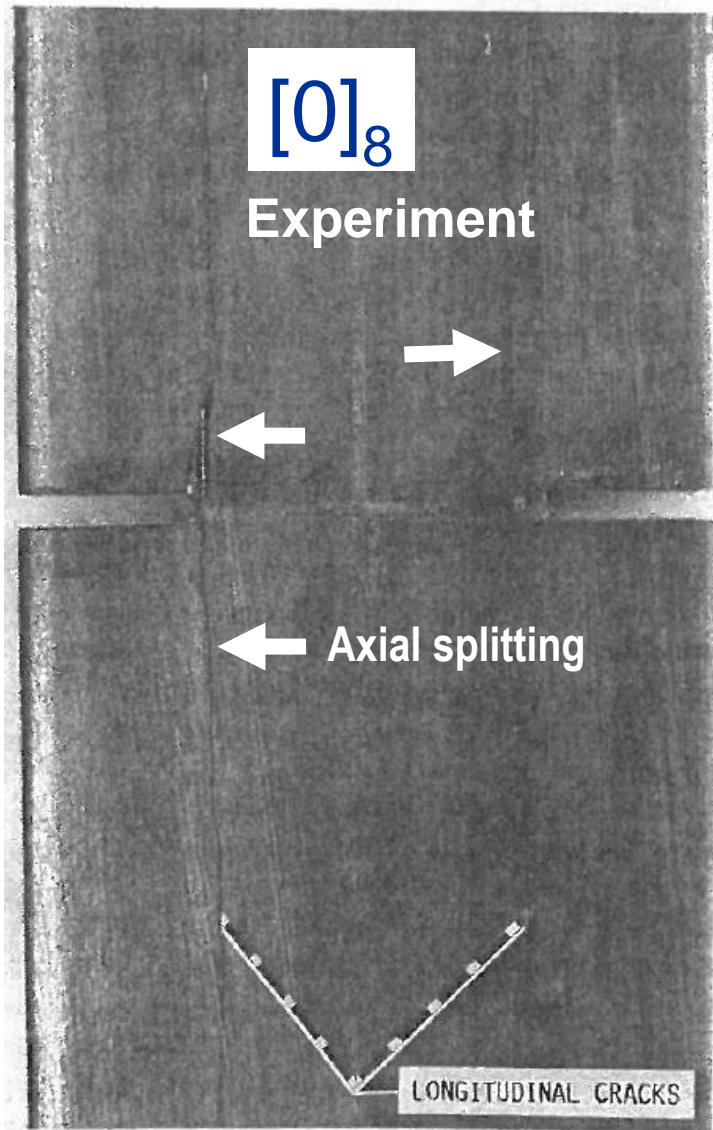
Assuming matrix and interface are isotropic strength materials




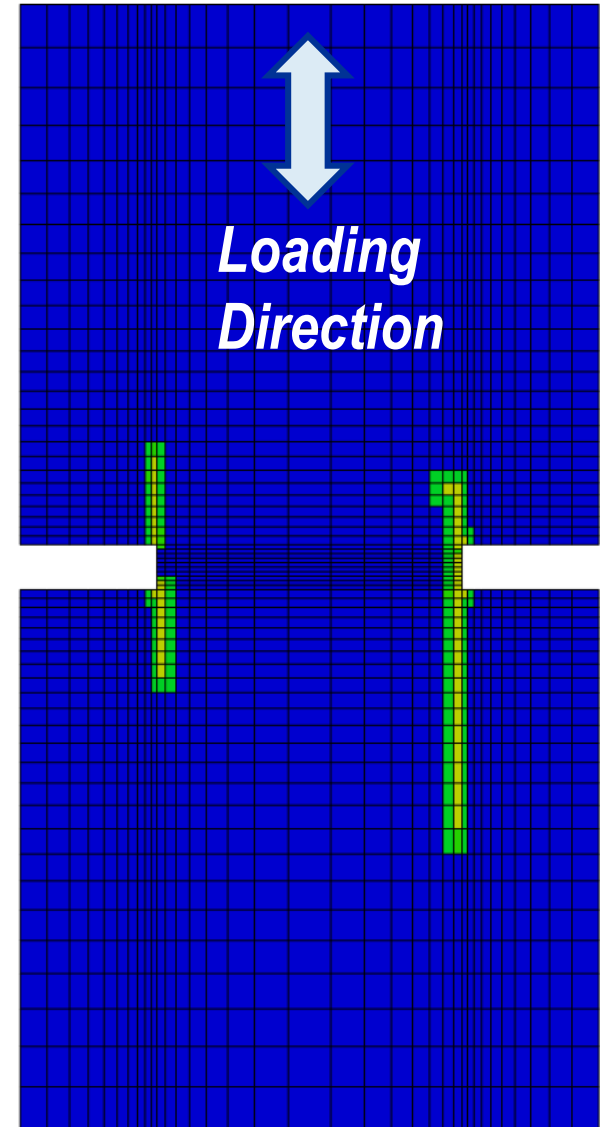
# 0° Double-Notched Tensile Specimen

Failure mode showed axial splitting of matrix

FEAMAC/CARES analysis was for a single ply to speed computation



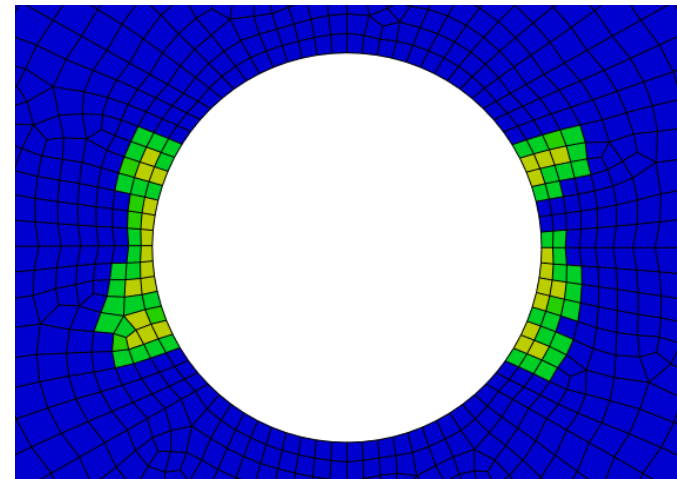
  
*Fiber  
Direction*



# 0° Double-Notched vs: Central-Hole Tensile Specimen

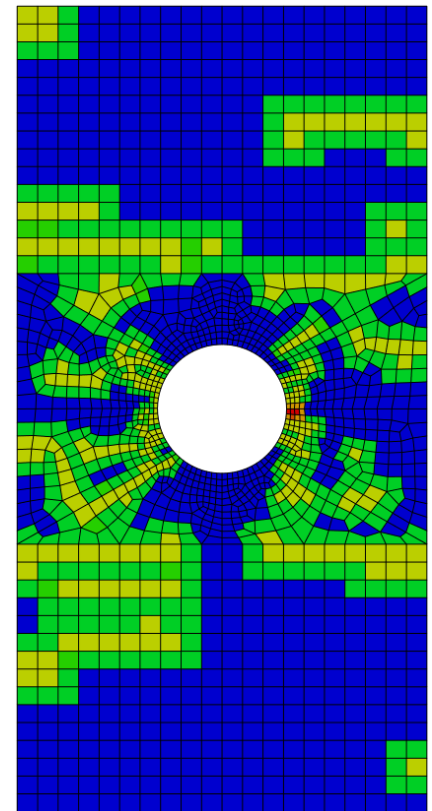
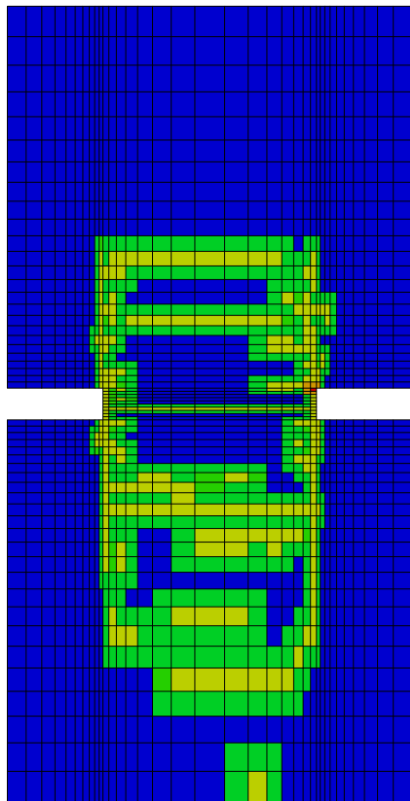
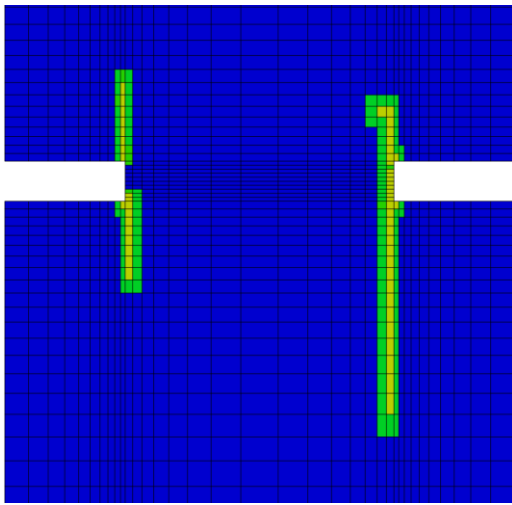


*Loading Direction*



Early matrix damage

Matrix damage  
progression





# *Work in Progress: Weibull Size Effect Demo*

## 0° Unidirectional Ply Flexural Specimen Simulations

### Objective

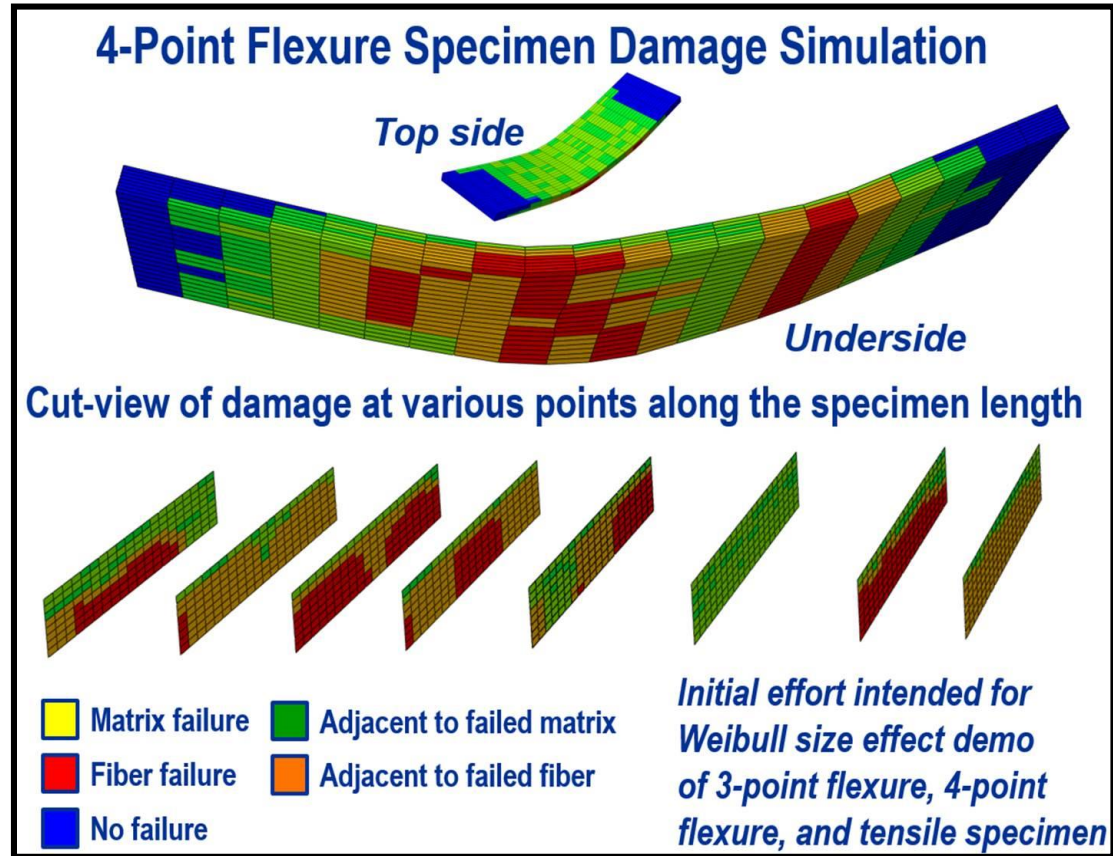
- Finite element models using solid elements of 3-point bending flexure, 4-point bending flexure, and a tensile specimen have been prepared.

### Approach

- Demonstrate that FEAMAC/CARES is functional with Abaqus solid elements (not been verified previously)
- Progressive damage simulations of a unidirectional fiber oriented CMC are on-going.

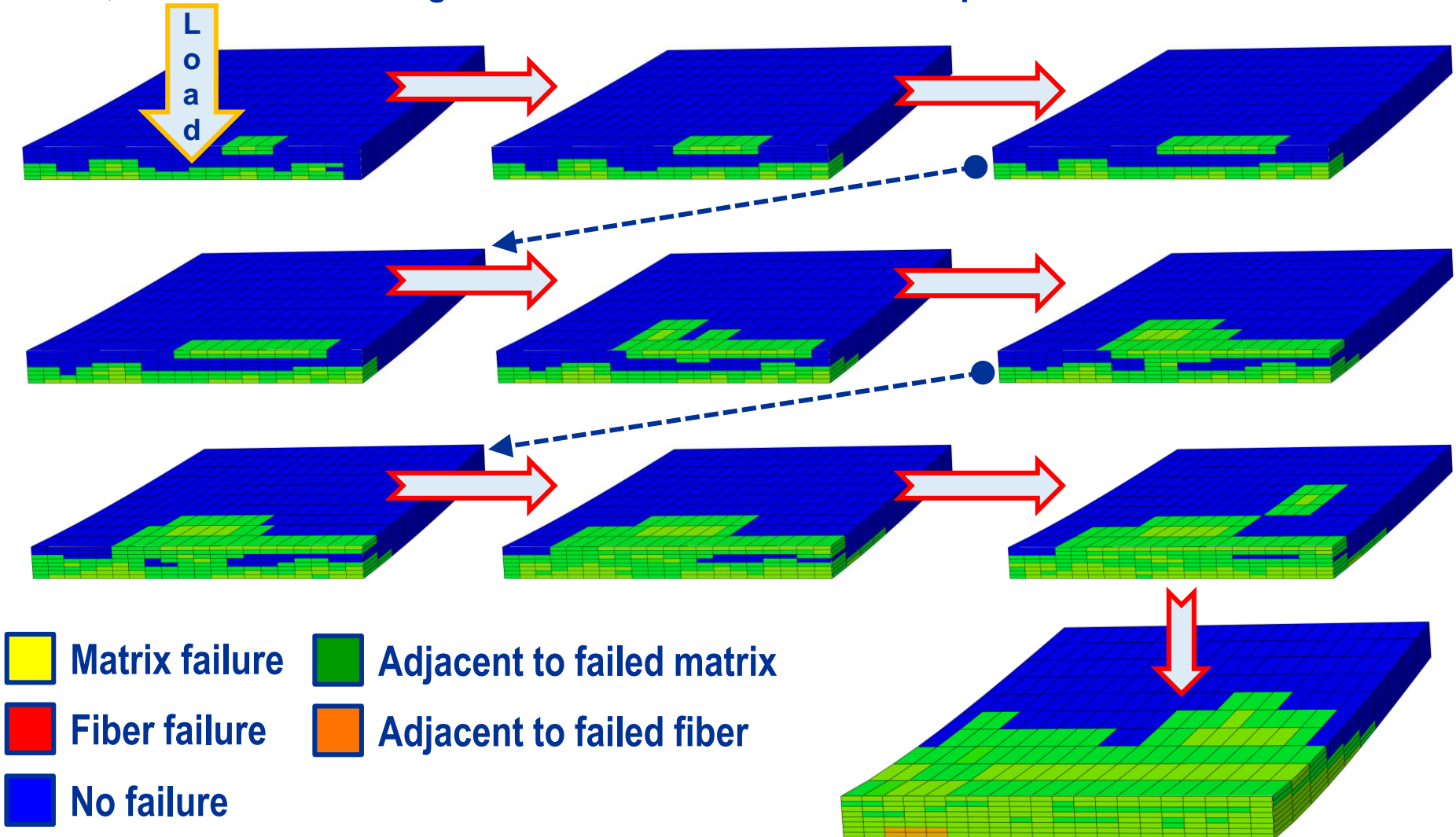
### Next Steps

- The models will be interrogated regarding predictions on Weibull size effect comparing the three specimen geometries



# Cut view of 3-pt bend bar showing damage at mid-plane

Damage propagates through the thickness on the tensile side but on the compression side it propagates laterally across the width. The compression failure criterion was not active, so failure is coming from shear failure on the unit sphere in the tensile domain.





# Conclusions

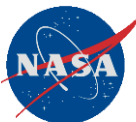
- Progressive damage simulation of composite structures incorporating probabilistic material strength models is possible with the FEAMAC/CARES code
- The Unit Sphere multiaxial model was used to predict the strength response of a SiC-RBSN composite for various fiber orientations under uniaxial tension
- Reasonable correlation to matrix cracking strength experimental data was achieved assuming the matrix was an isotropic material with  $m \approx 5$ , and assuming residual stresses from thermal processing were present
- Brittle behavior vs: non-brittle failure (*graceful failure*) demonstrated
- Localized damage modes at stress concentration features shown
- *Component level probability of first damage initiation event tracked at each load increment*

***Future work: Try to simulate EBC failure modes ?***

## Acknowledgement

This work was funded by the NASA Transformative Tools and Technologies Program

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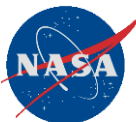


# *Extra Material*



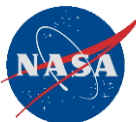
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# Abstract:

Reported here is a coupling of two NASA developed codes: CARES (Ceramics Analysis and Reliability Evaluation of Structures) with the MAC/GMC (Micromechanics Analysis Code/ Generalized Method of Cells) composite material analysis code. The resulting code is called FEAMAC/CARES and is constructed as an Abaqus finite element analysis UMAT (user defined material). Here we describe the FEAMAC/CARES code and an example problem (taken from the open literature) of a laminated CMC in off-axis loading is shown. FEAMAC/CARES performs stochastic-strength-based damage simulation response of a CMC under multiaxial loading using elastic stiffness reduction of the failed elements.



# Some References:

**Aboudi, J.; Arnold, S.M.; and Bednarczyk, B.A. (2013) Micromechanics of Composite Materials: A Generalized Multiscale Analysis Approach, Elsevier, Oxford, UK.**

**Aboudi, J; Pindera, M.J.; and Arnold, S.M. (2003): Higher-Order Theory for Periodic Multiphase Materials With Inelastic Phases. Int. J. Plast., vol. 19, pp. 805–847.**

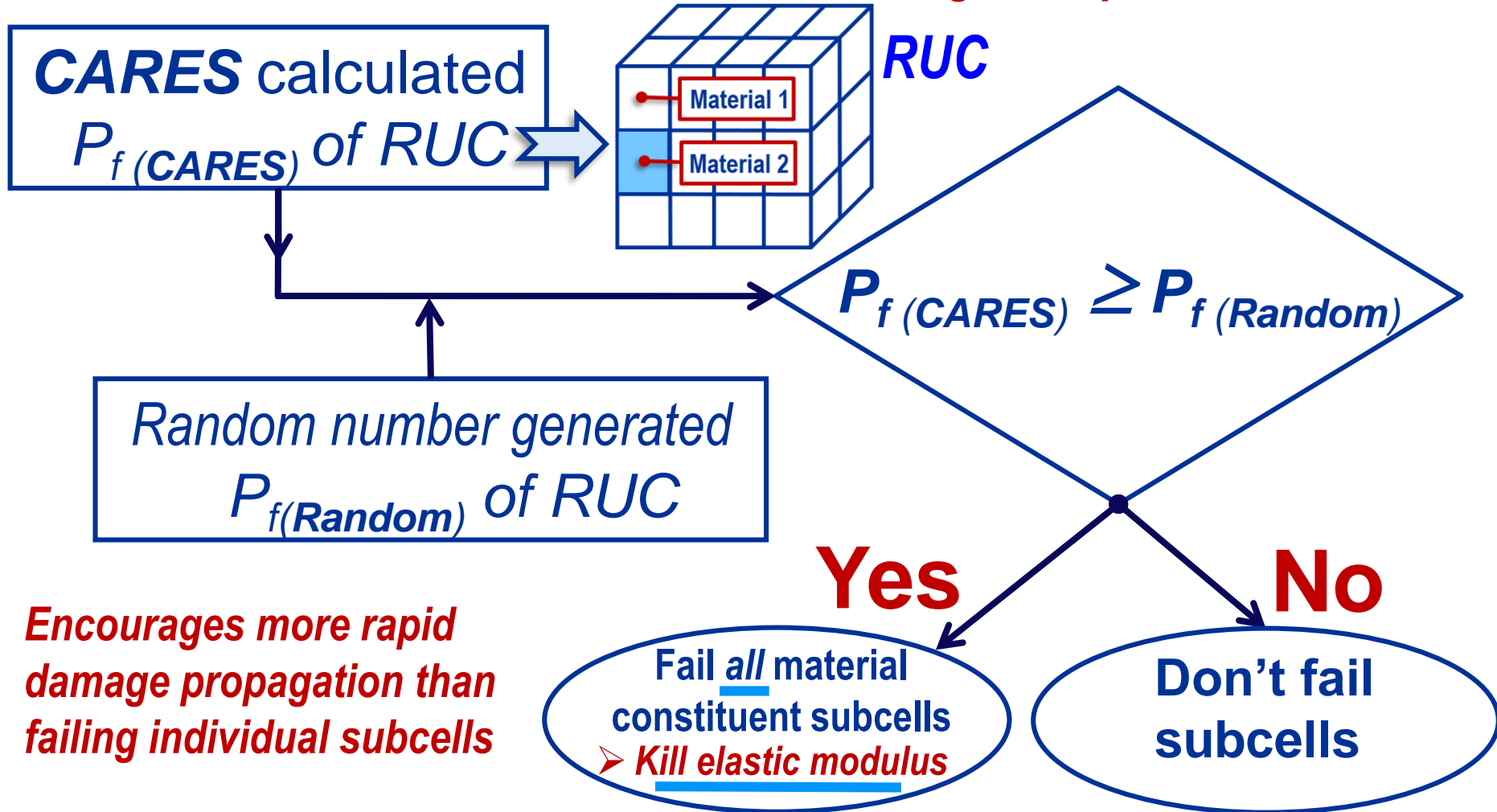
**Nemeth, Noel, N.: “Unit-Sphere Multiaxial Stochastic-Strength Model Applied to a Composite Material.” Journal of Composite Materials Vol. 48(27), pp. 3395-3424, November 2014.**

**Nemeth, Noel, N.: “Probability Density Distribution of the Orientation of Strength-Controlling Flaws From Multiaxial Loading Using the Unit-Sphere Stochastic Strength Model for Anisotropy.” International Journal of Fracture, Vol. 185, Issue 1-2, pp. 97-114, January, 2014.**

**Nemeth, Jadaan, Gyekenyesi.: “Lifetime Reliability Prediction of Ceramic Structures Under Transient Thermomechanical Loads.” NASA/TP-2005-212505, 2005.**

# Progressive Damage Criterion

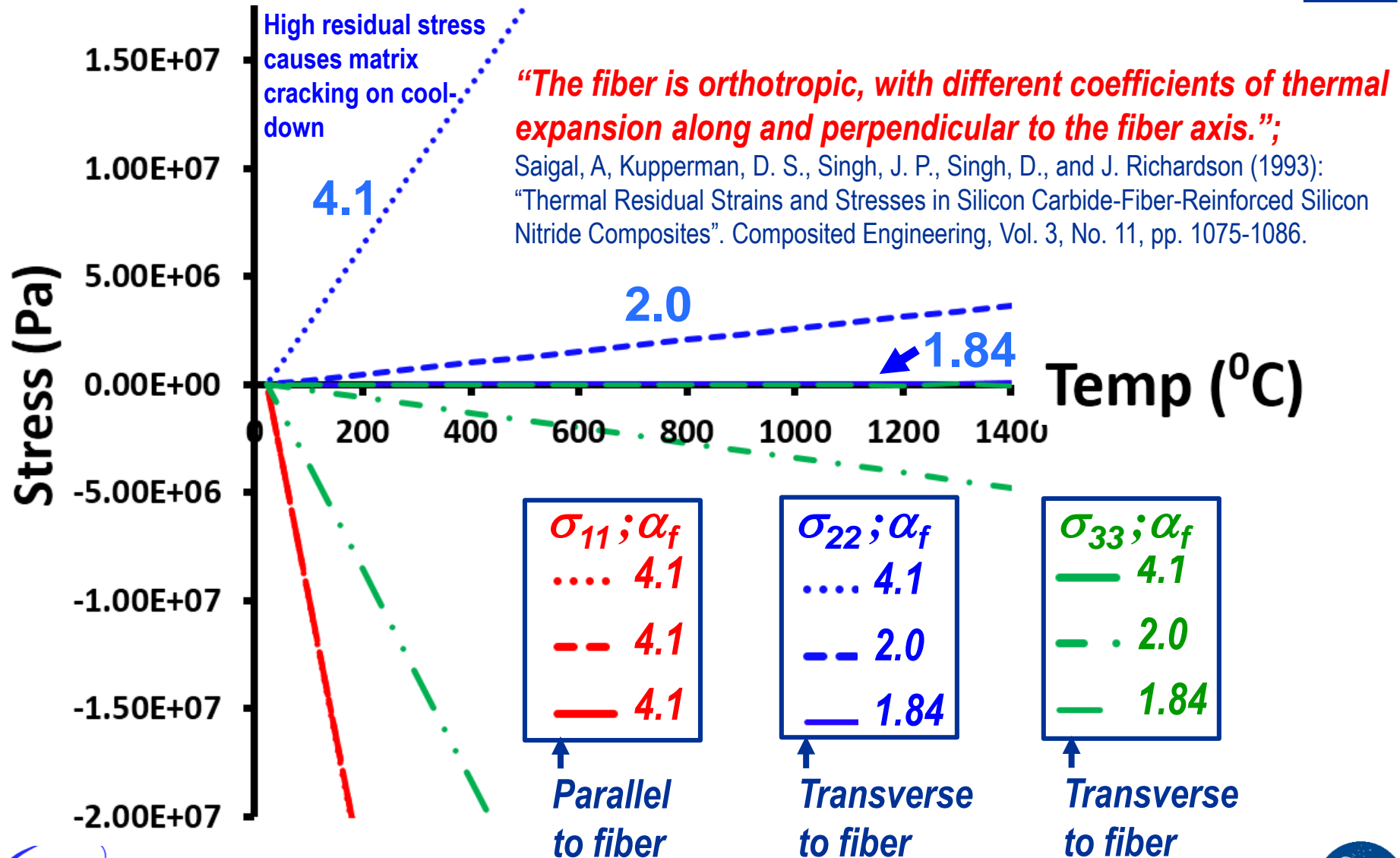
*Calculate failure probability,  $P_f$ , for each material constituent of the RUC associated with an element integration point*

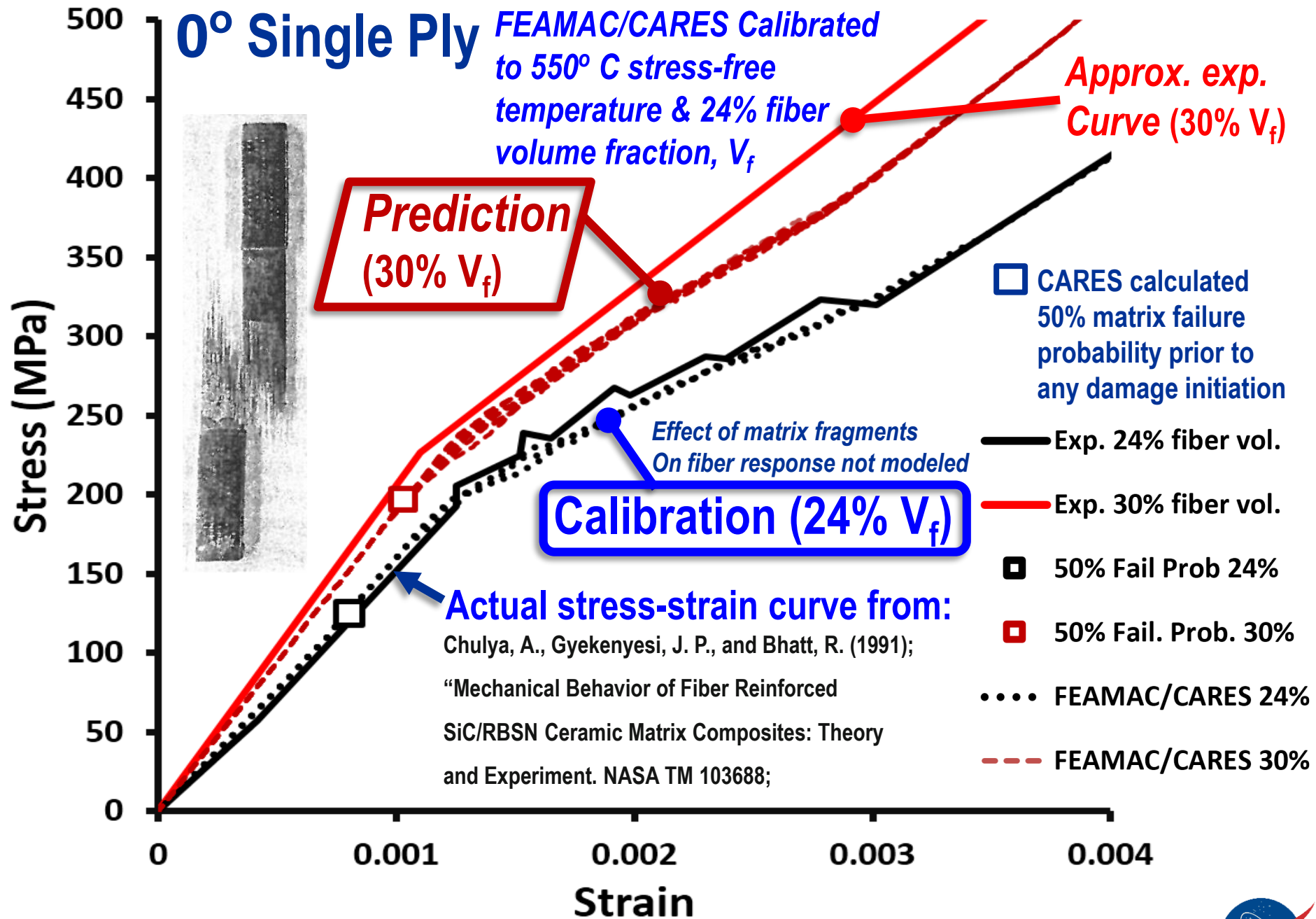


*Encourages more rapid damage propagation than failing individual subcells*

# Residual matrix stresses after cool-down from temperature

- Effect of anisotropic fiber-thermal-expansion-coefficient,  $\alpha_f$  on RUC



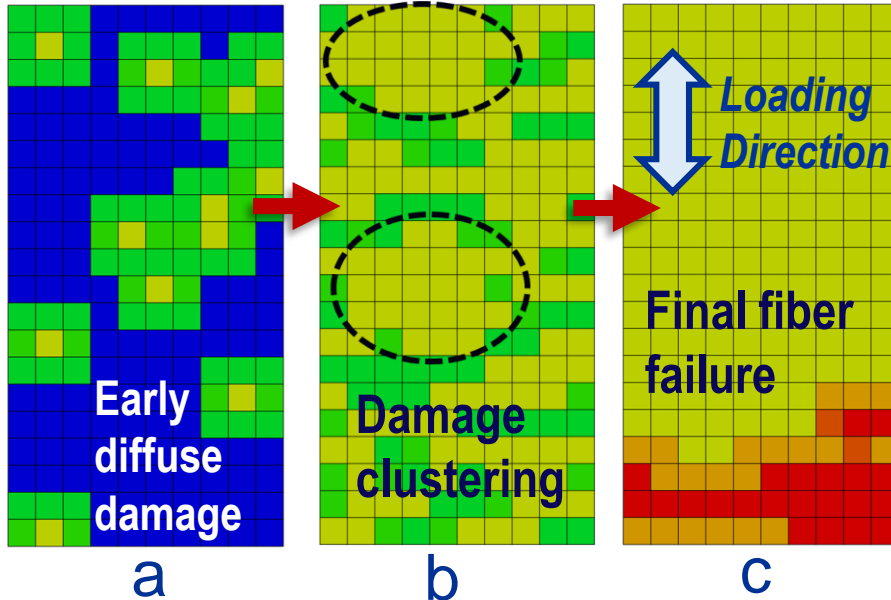




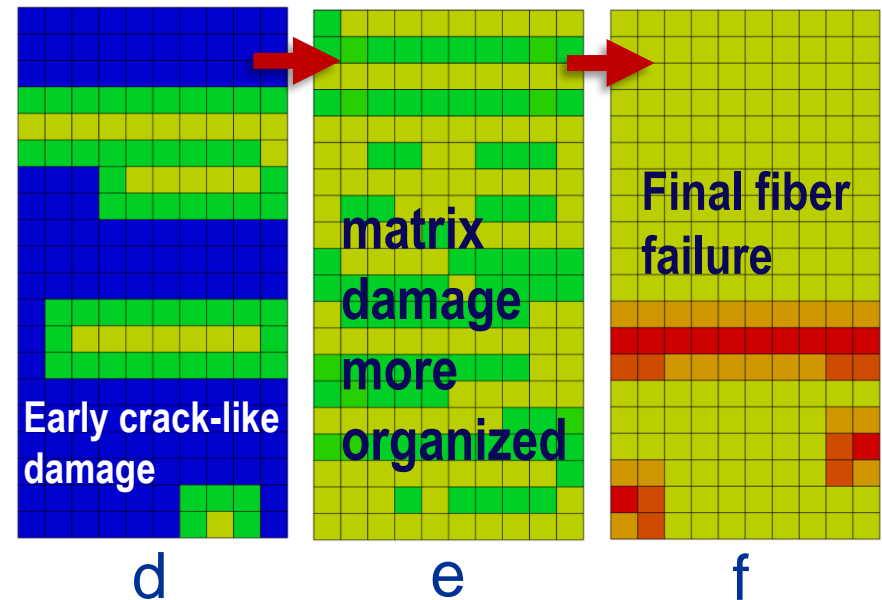
# 0° single ply tensile specimen

Progression of damage in FE model of a unidirectional ply under longitudinal loading

## Not Adjusted



## Automaton Adjusted

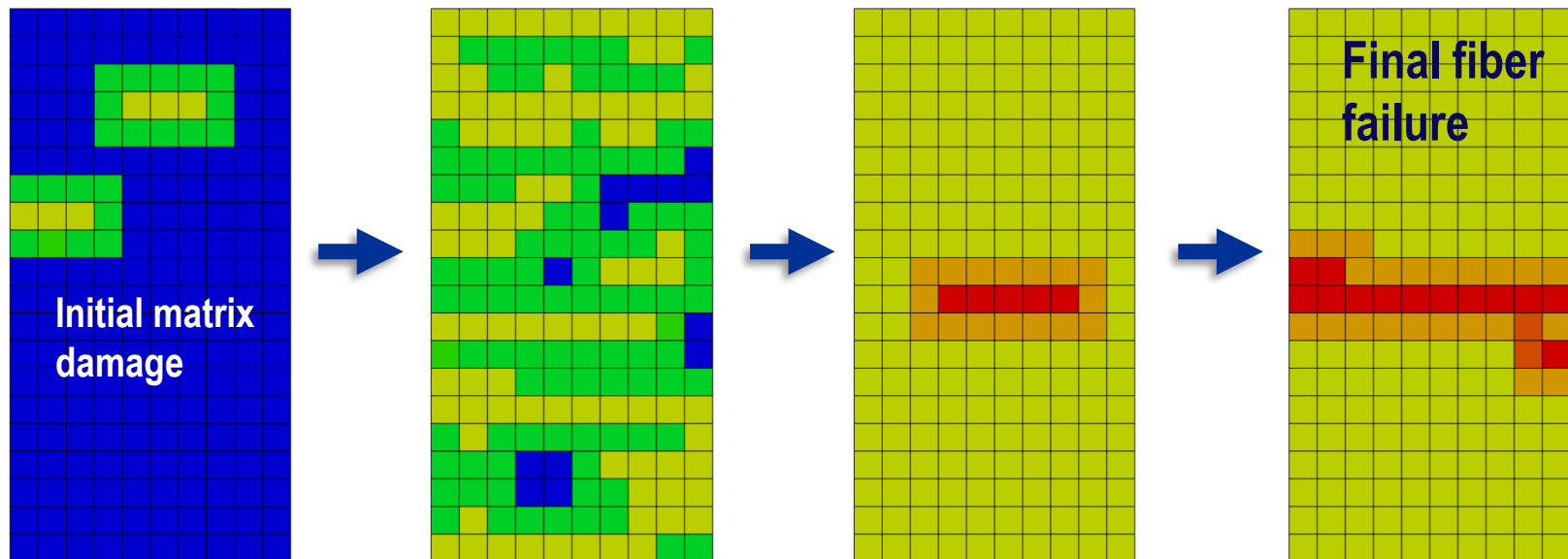
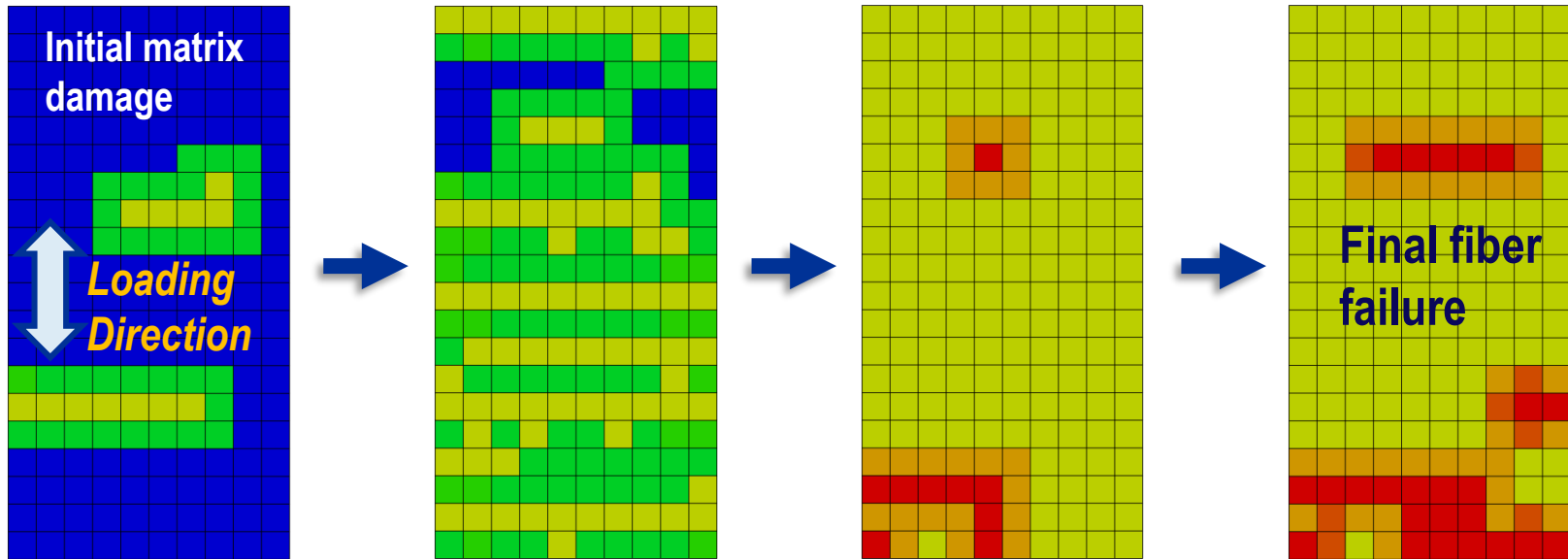


*(a) and (d)* ; early matrix damage

*(b) and (e)* ; progression to substantial matrix damage

*(c) and (f)* ; final composite failure (fiber failure)

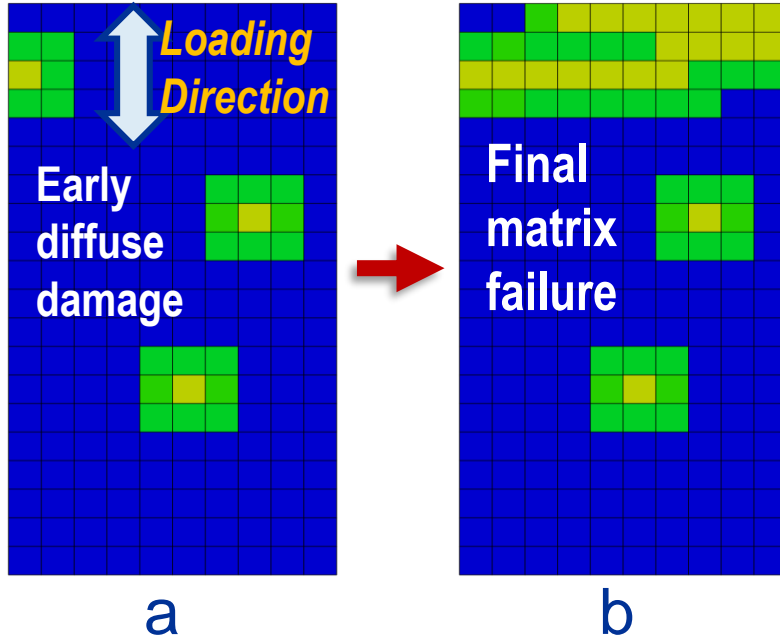
# Damage progression of 0° tensile specimen - two trials (undeformed plot)



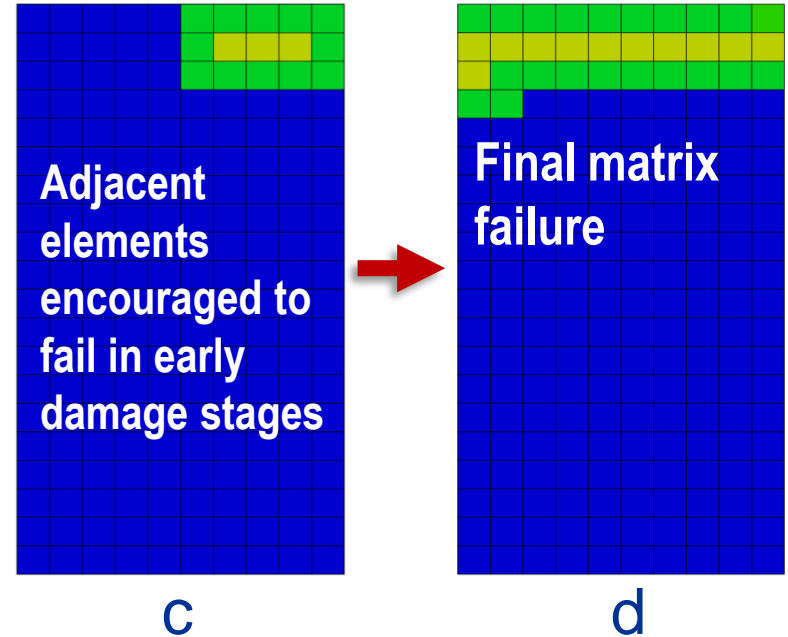
# 90° single ply tensile specimen

Progression of damage in FE model of a unidirectional ply under *transverse* loading

## Not Adjusted

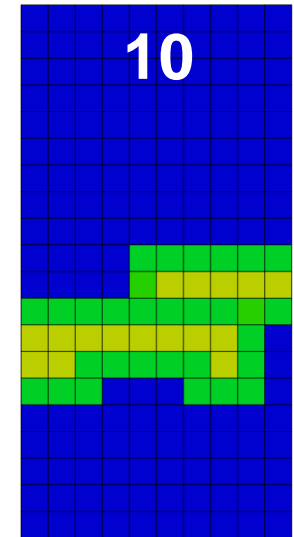
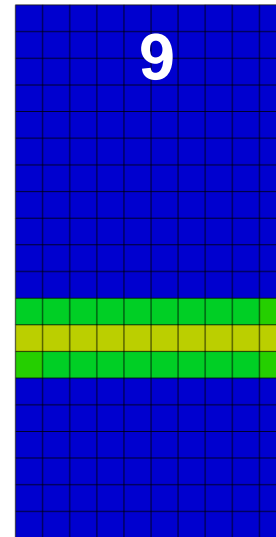
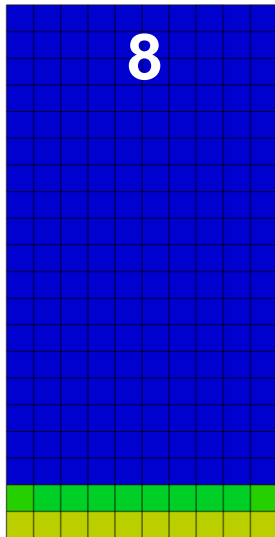
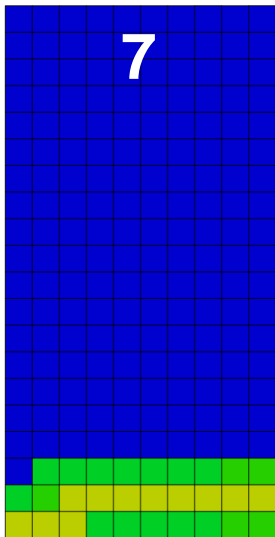
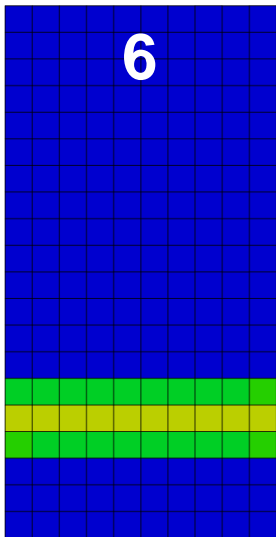
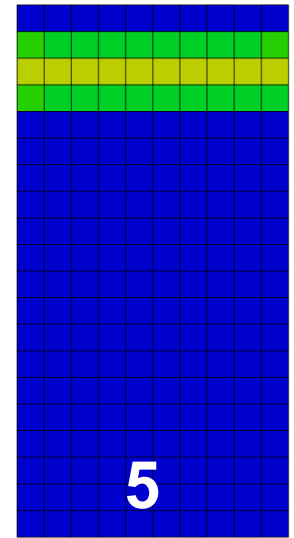
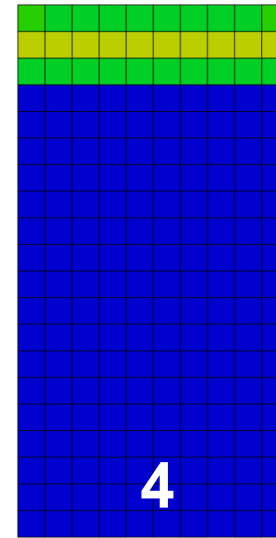
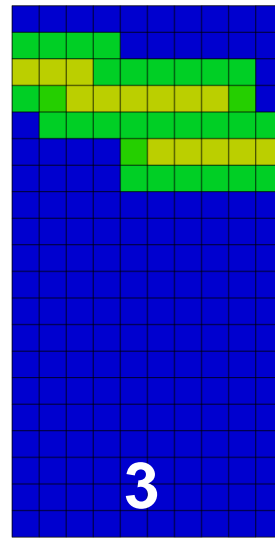
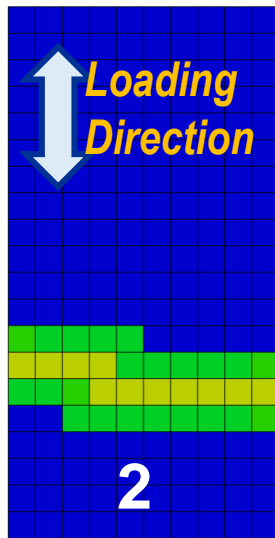


## Automaton Adjusted



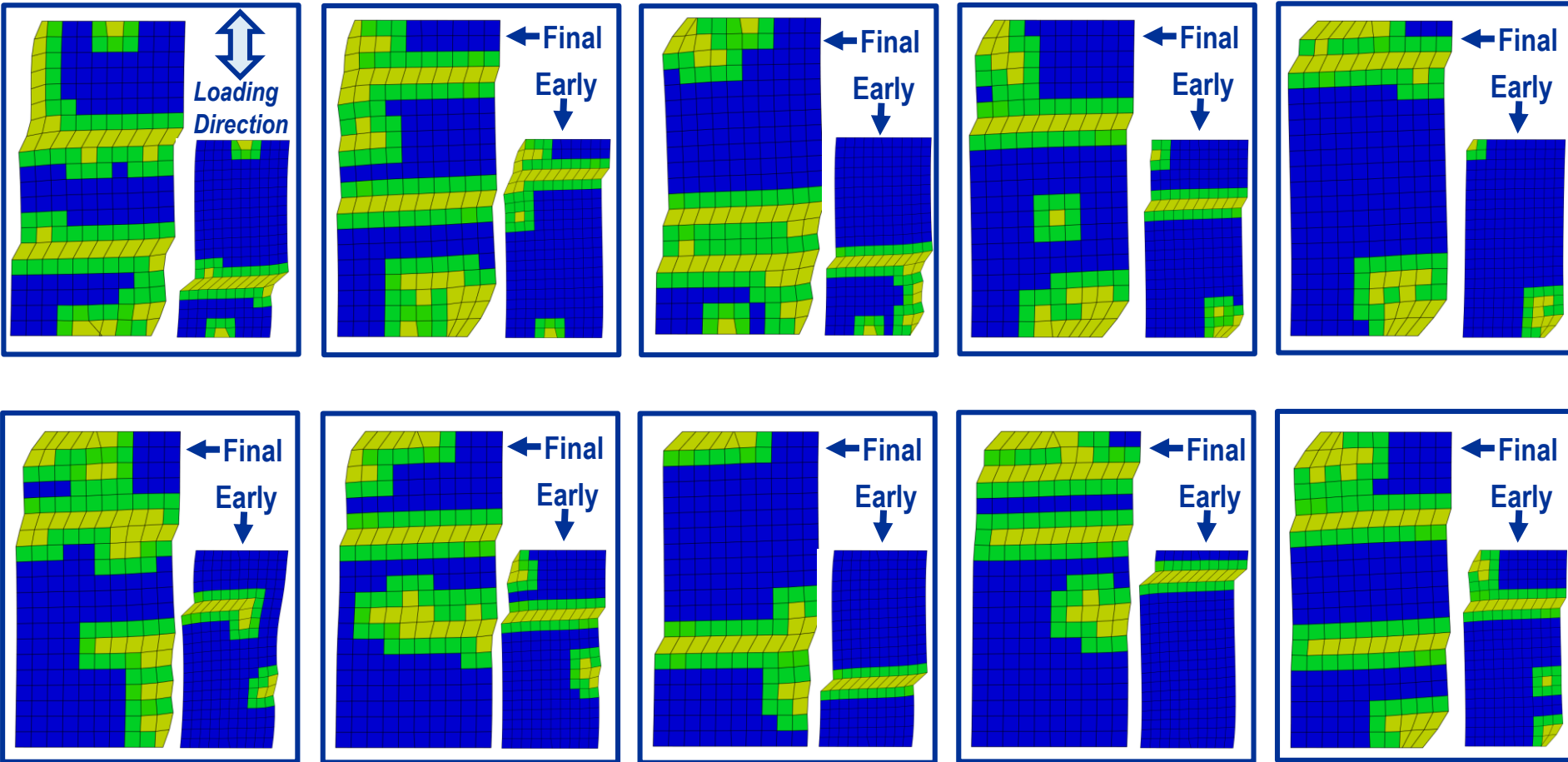
(a) and (c) ; early matrix damage  
(b) and (d) ; final composite failure (matrix failure)

# 90° Tensile specimen *at final failure for 10 trials* – Undeformed plots



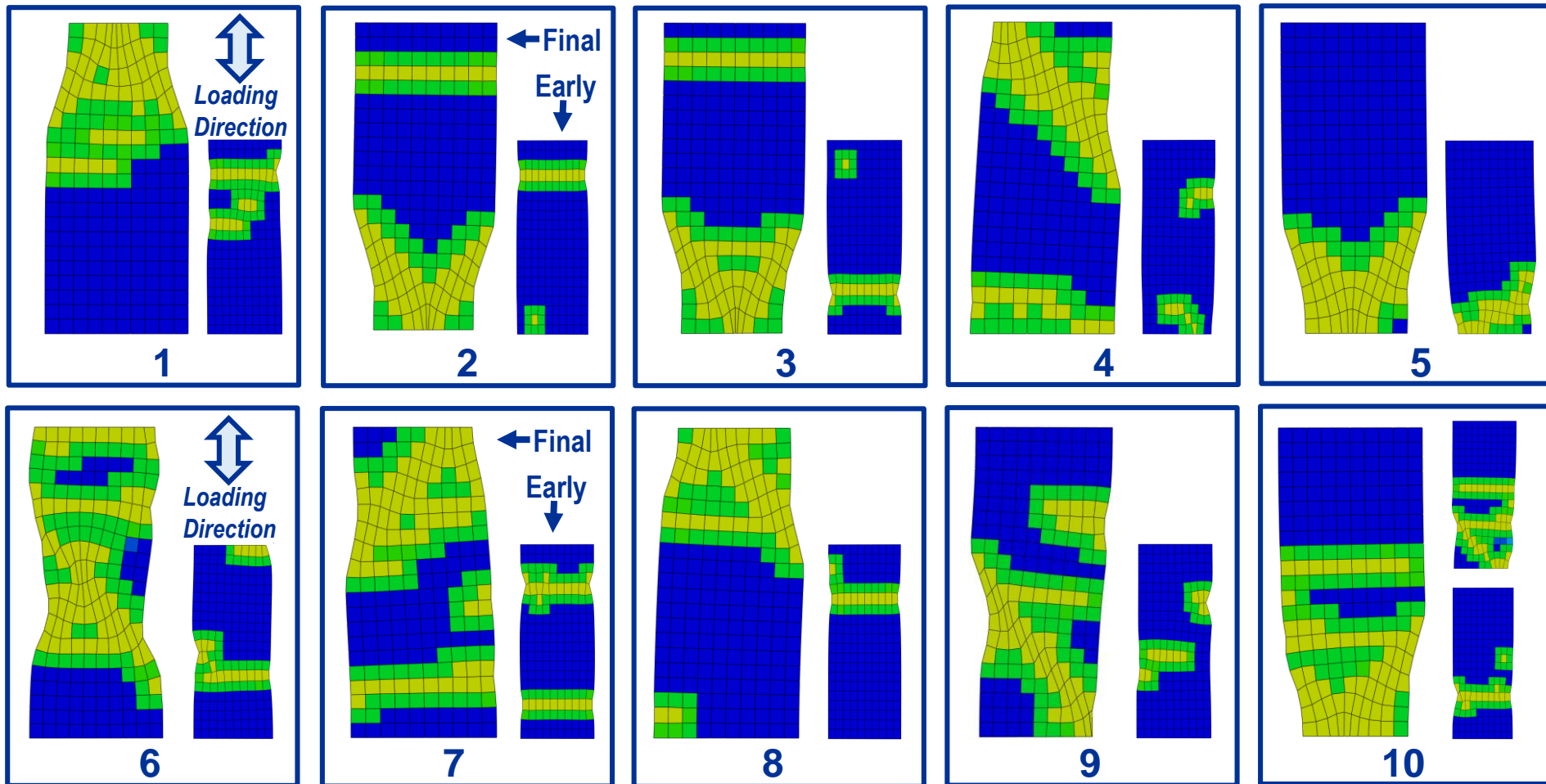
# 10<sup>0</sup> off-axis tensile specimen; 10 trials at final (matrix) failure; deformed plots

- Edges are allowed to freely deform (warp) on cool-down
- *After cool-down*; bottom edge fixed in loading direction when displacement load applied
- *After cool-down*; single node along top edge (middle) fixed in direction perpendicular to displacement direct.

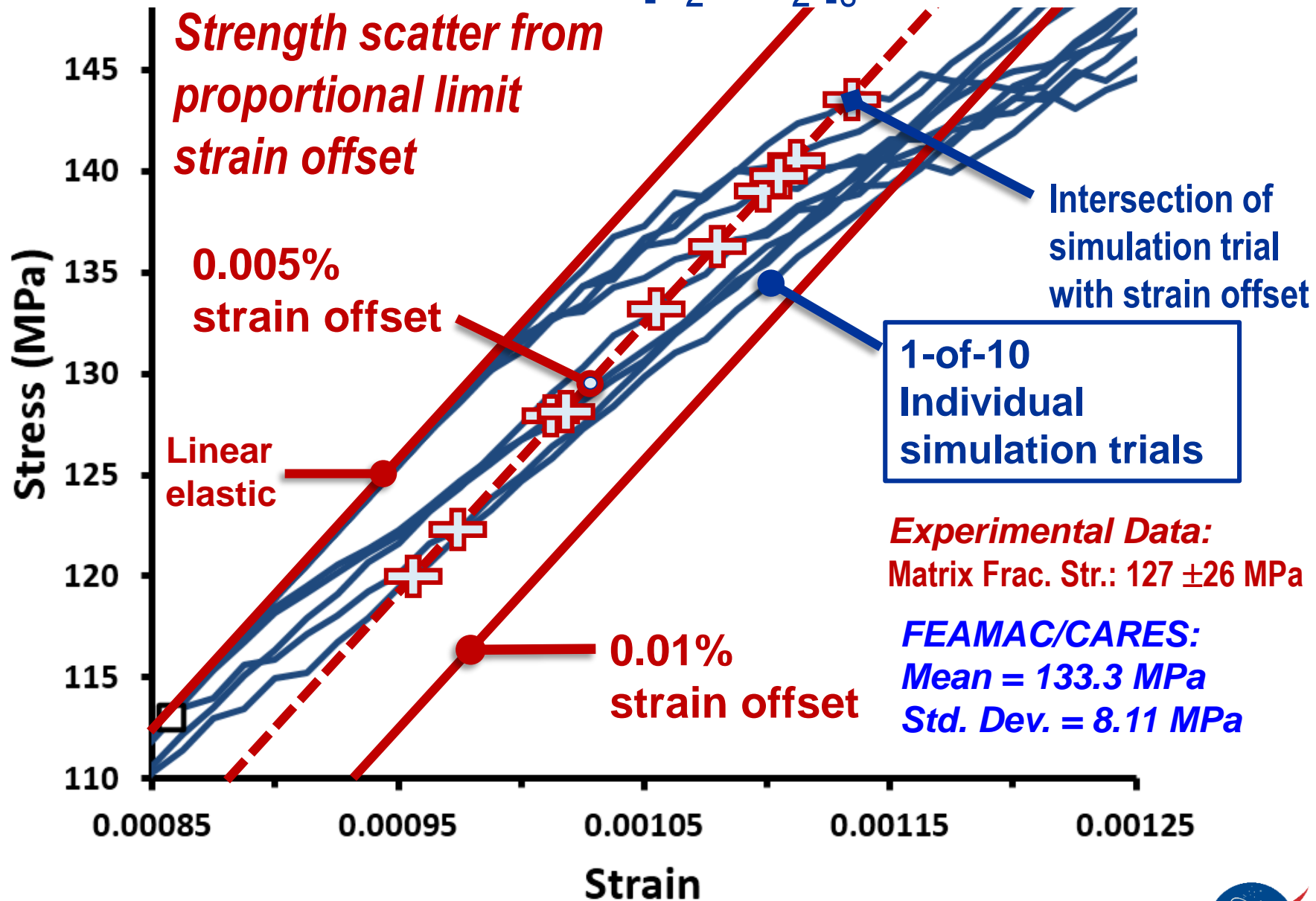


# For $[+45/-45]_s$ Fiber Orientation; 10 trials at final (matrix) failure; deformed plots

FEAMAC/CARES analysis was for four plies (+45/-45/-45/+45) to speed computation

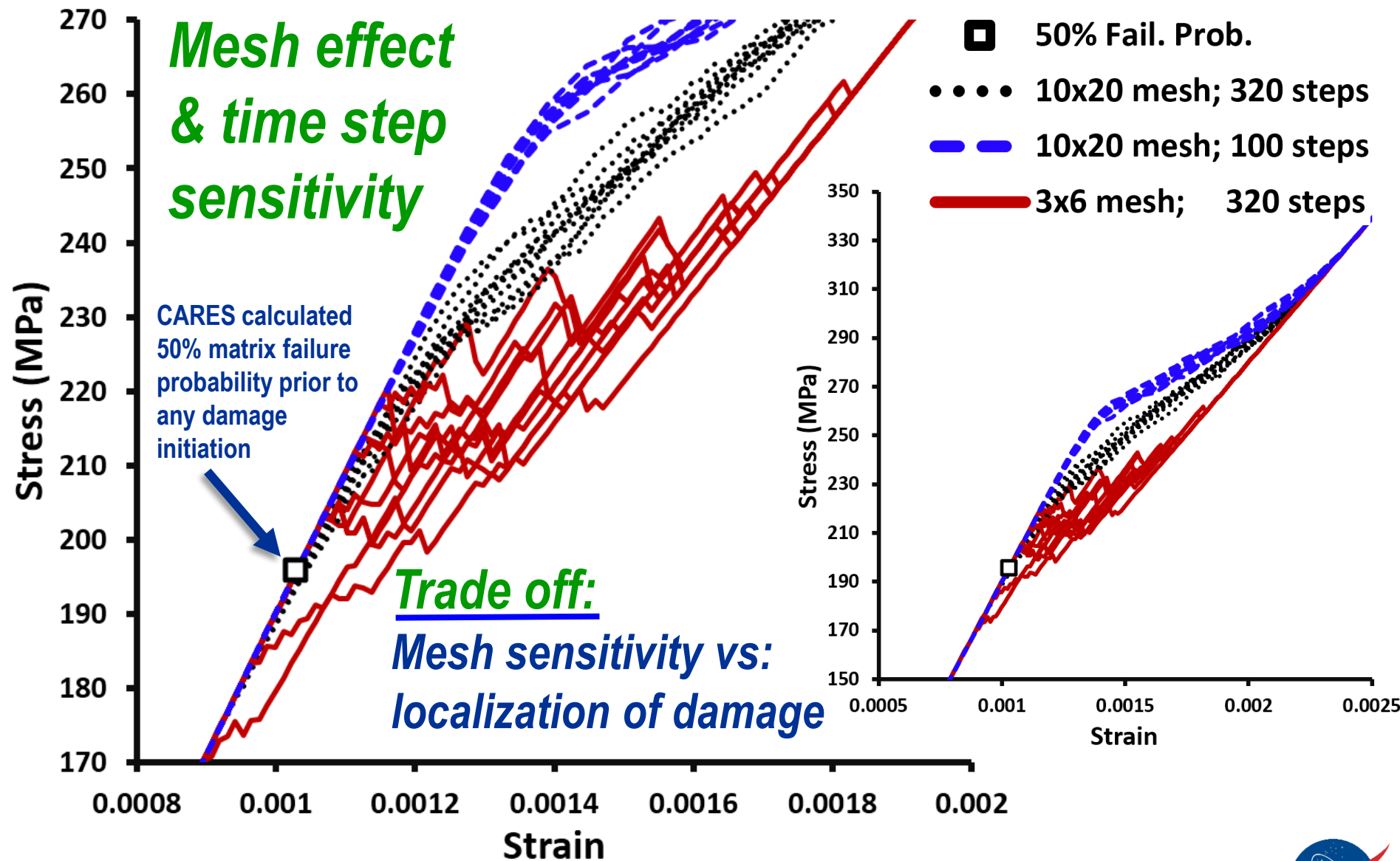


# Prediction for Ten Trials for $[0_2/90_2]_s$ Fiber Orientation





# 0° single ply tensile specimen *(Load parallel to fiber axis)*



# Unit Sphere Multiaxial (Batdorf) Model:

Puts linear elastic fracture mechanics into Weibull weakest-link theory

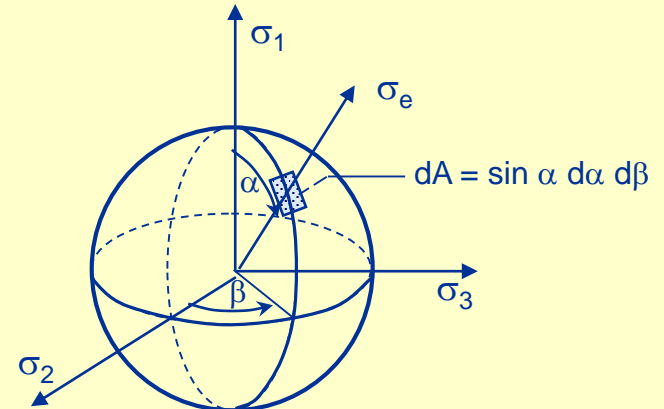
- **Incremental failure probability is the product of two probabilities:**

$$\Delta P_f = P_1 \cdot P_2$$

$P_1$  = Probability of the existence of a crack having a critical strength between  $\sigma_c$  and  $\sigma_c + \Delta\sigma_c$  in the incremental volume  $\Delta V$

$P_2$  = Probability a crack having a critical strength of  $\sigma_c$  will be oriented in a direction such that it will fail under the applied multiaxial stress state

$P_2$  involves Integration of an equivalent stress  $\sigma_e$ , where  $\sigma_e \geq \sigma_c$ , over the surface of a unit radius sphere (all possible flaw orientations) divided by the total surface area of the unit radius sphere



$\sigma_e$  is a function of an assumed crack shape and multiaxial fracture criterion

## Mixed-Mode Fracture Criteria:

- Normal stress (shear-insensitive cracks)
- Maximum tensile stress
- Total coplanar strain energy release rate
- Noncoplanar (Shetty)

## Flaw Shapes:

- Griffith crack
- Penny-shaped crack

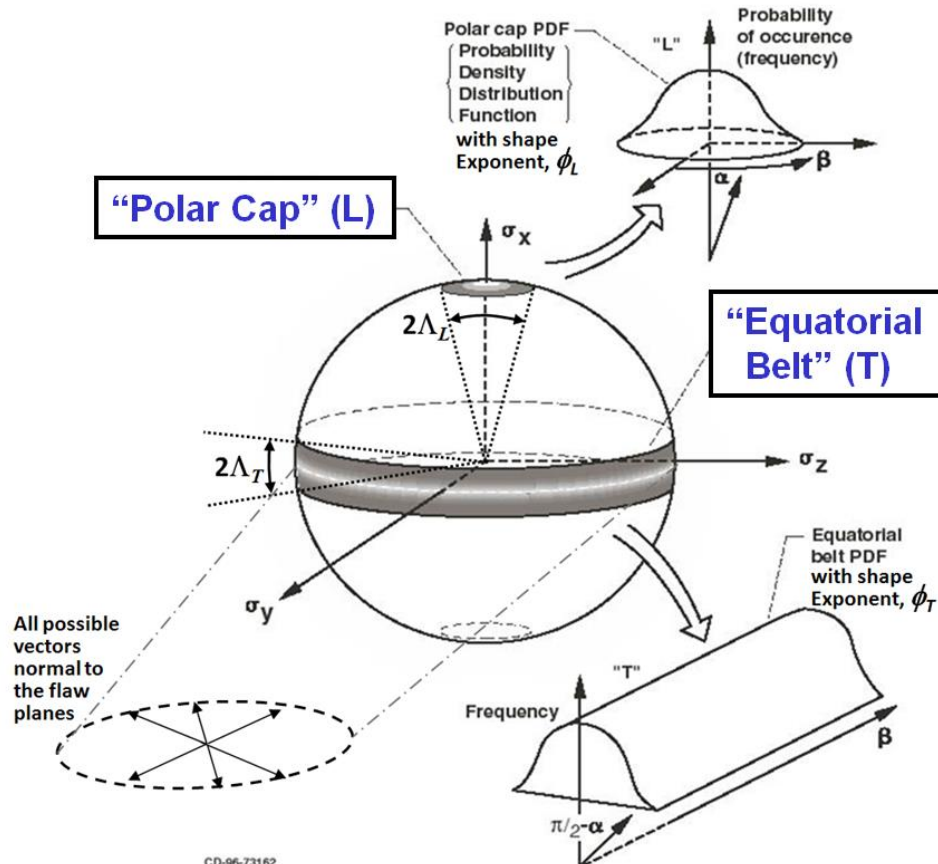
- **Component failure probability:**

$$P_f = 1 - \exp \left\{ - \int_V \left[ \int_0^{\sigma_e} P_1(\sigma_c) P_2(\sigma_c) d\sigma_c \right] dV \right\}$$

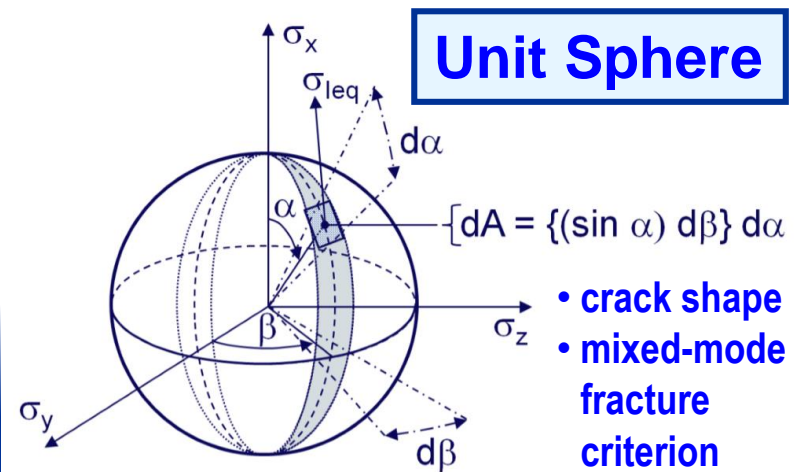
# Unit Sphere Stochastic-Strength Multiaxial Failure Criterion model

## ➤ Two models for transverse isotropy

### • Flaw / Fracture-Plane Orientation Anisotropy

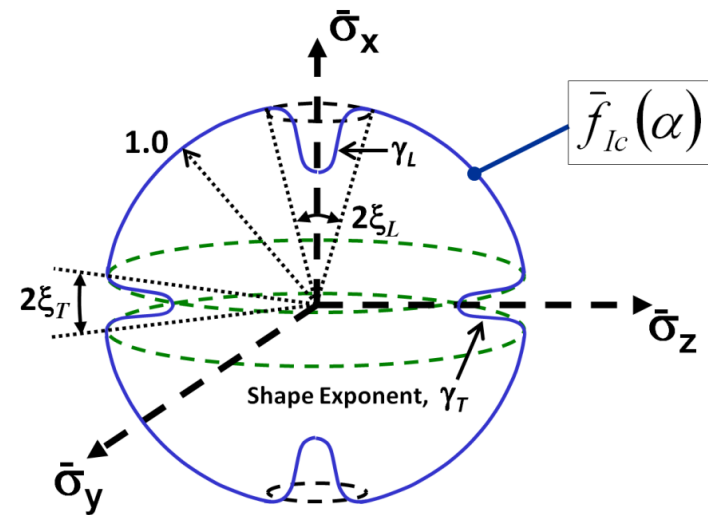


Failure probability  $\rightarrow$  surface area of a unit radius sphere (all possible flaw orientations), where equivalent mode I stress ( $\sigma_{Ieq}$ ) exceeds critical mode I strength ( $\sigma_{Ic}$ ), divided by the total surface area of the unit radius sphere



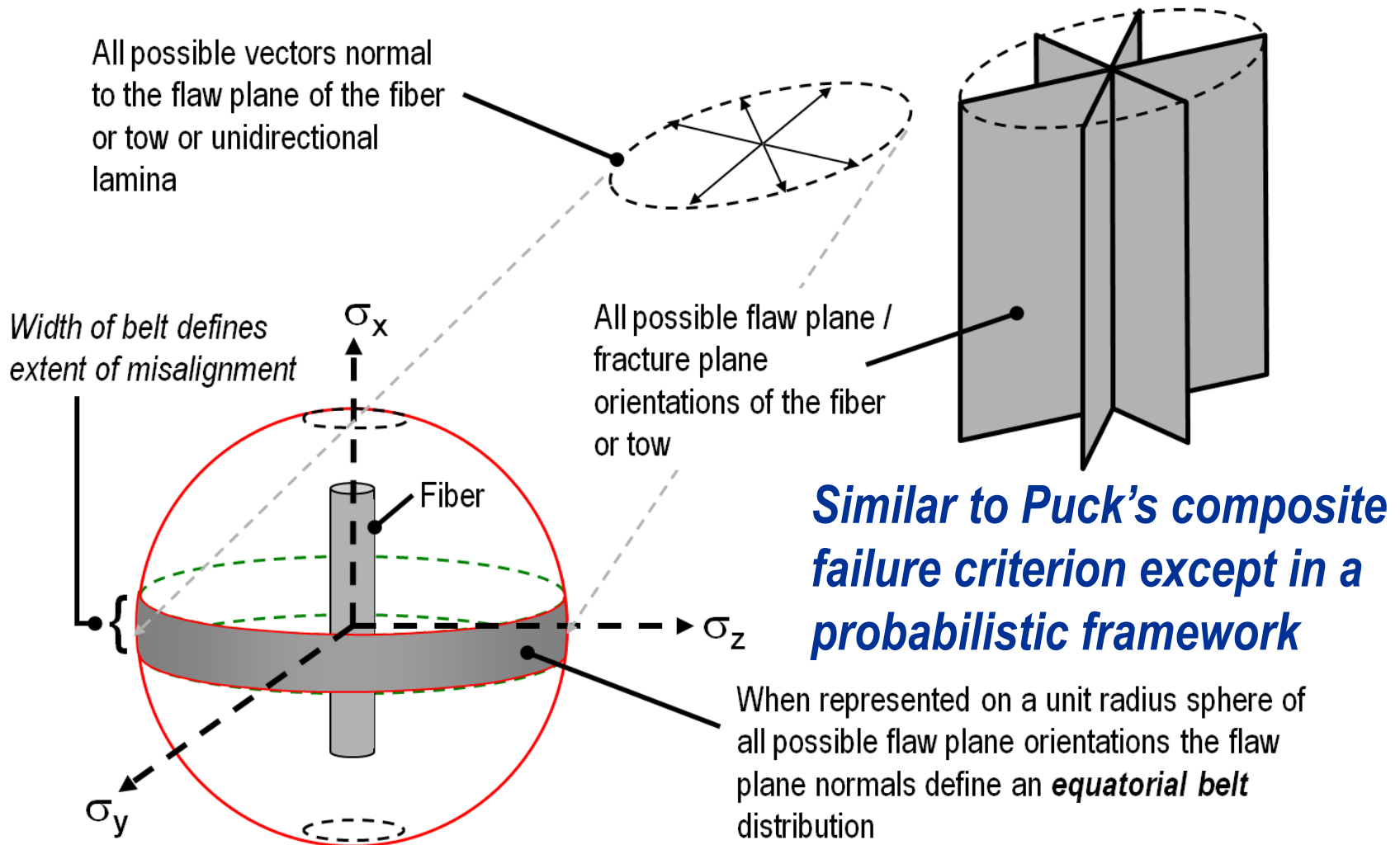
### • Strength Orientation Anisotropy

$\sigma_{Ic}$  or  $K_{Ic}$  varies with orientation

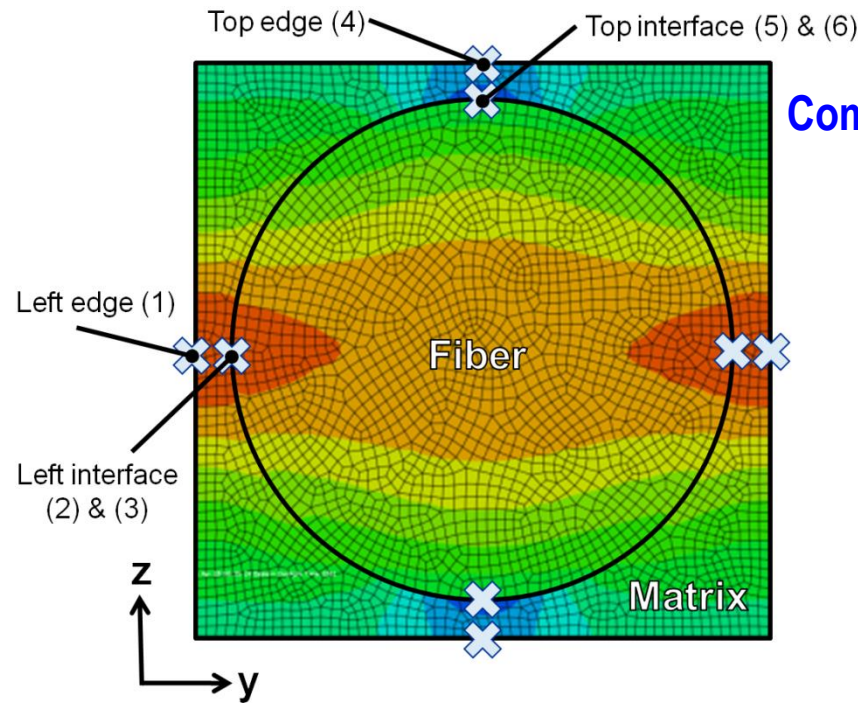


Nemeth, N. N.: "Unit-Sphere Multiaxial Stochastic-Strength Model Applied to a Composite Material." Journal of Composite Materials Vol. 48(27), pp. 3395-3424, November 2014.

# Anisotropic Unit Sphere model defined in a material coordinate system reference frame

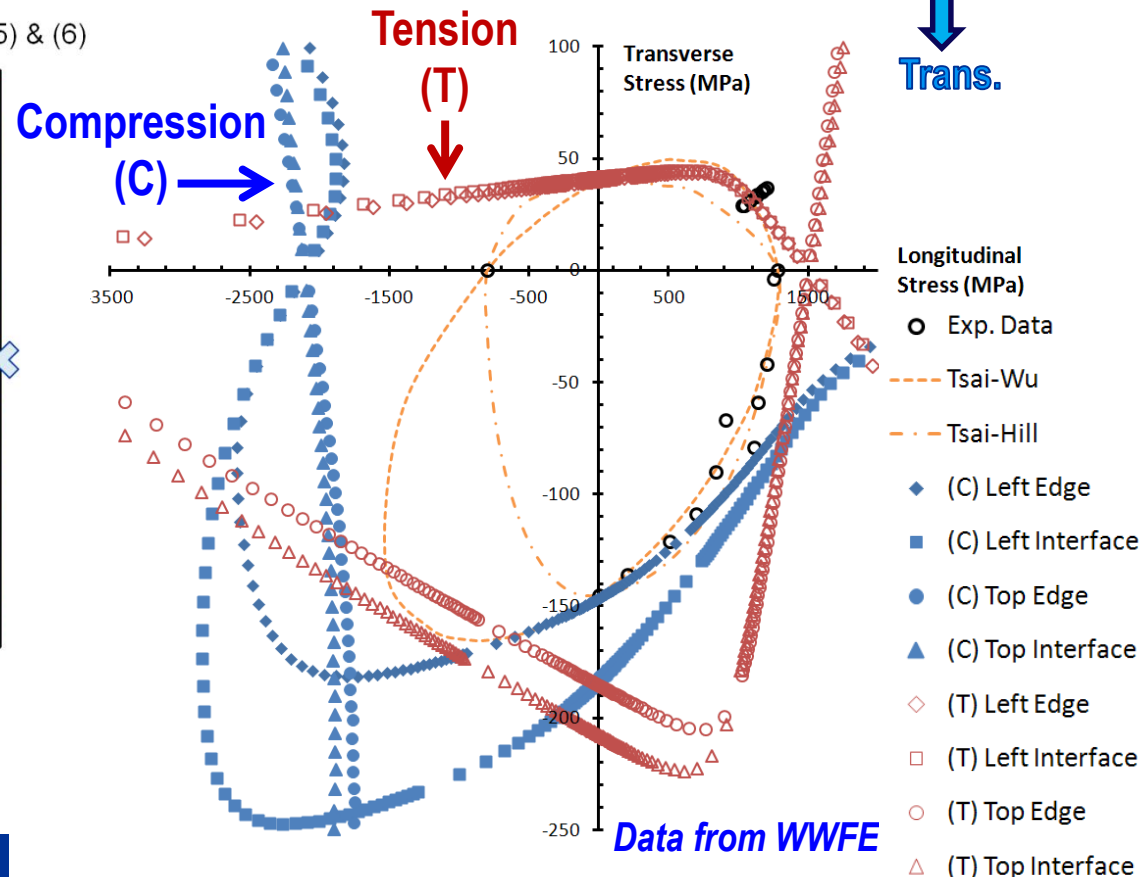


# Example of a biaxial failure envelope at 50% probability of failure ( $P_f$ ) for a PMC unit cell



**FE model of a fiber-in-matrix unit cell**  
(Sampled points indicated with  $\otimes$ )

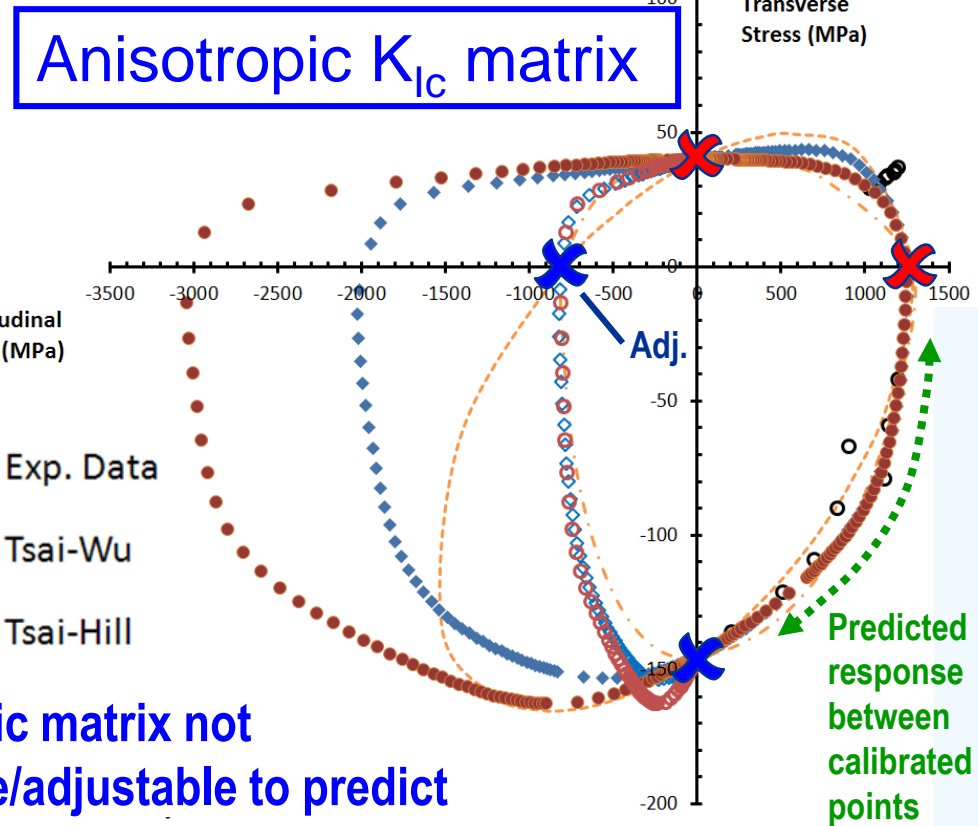
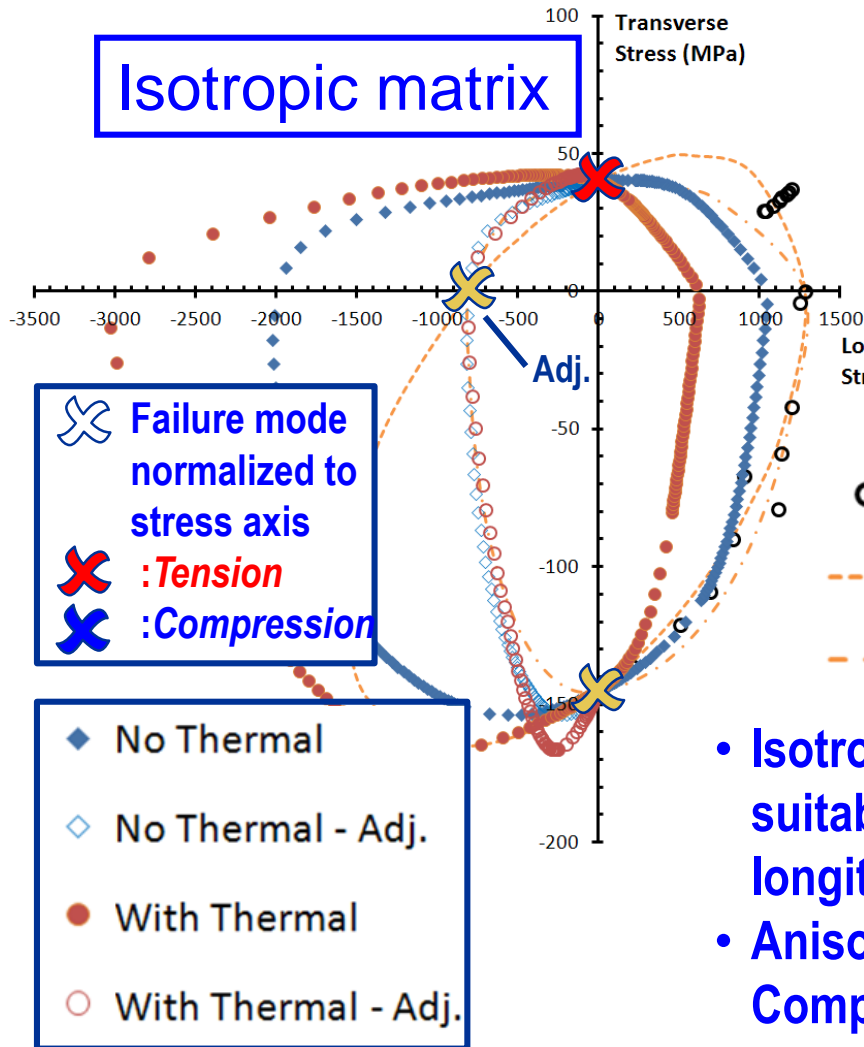
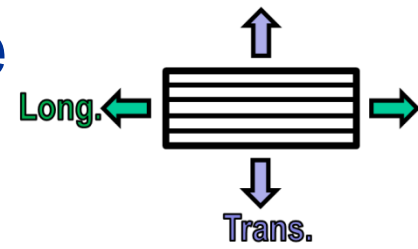
Nemeth, N. N.: "Unit-Sphere Multiaxial Stochastic-Strength Model Applied to a Composite Material." *Journal of Composite Materials* Vol. 48(27), pp. 3395-3424, November 2014.



**Tracking individual failure modes at sampled points for the matrix**  
(What mode is critical, where, and when)



# Biaxial failure envelope at 50% $P_f$ for a composite unit cell for all sampled points and failure modes (with and without thermal residual stresses)



- Isotropic matrix not suitable/adjustable to predict longitudinal strength
- Anisotropy in unit sphere
- Compares Tsai-Wu & Tsai-Hill
- Validates approach taken

Tsai/Wu/Hill curves come from the applied stresses on the composite

# Time-Dependent Life Prediction Theory - Slow Crack Growth and Cyclic Fatigue Crack Growth Laws

**Power Law:** - Slow Crack Growth (SCG)

$$\frac{da}{dt} = A K_{Ieq}^N$$

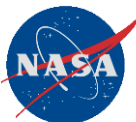
**Combined Power Law & Walker Law:** SCG and Cyclic Fatigue

$$\frac{da}{dt} = A_1 g K_{Ieq}^N + A_2 f_c (1-R)^Q K_{Ieq}^N$$



# Time-Dependent Life Prediction Theory - Slow Crack Growth and Cyclic Fatigue Crack Growth Laws with discrete time steps

Modeling individual time steps in the life prediction methodology enables simulating transient events such as turbine start-up/shut-down or atmospheric re-entry. A computationally efficient methodology has been developed that can extrapolate the reliability calculation for an arbitrary number of  $Z$  cycles – where each cycle is described by  $k$  number of time steps. This conceivably allows the coupling of other effects such as stiffness degradation and oxidation effects on the individual time steps and this can be accounted for interactively within the transient finite element and micromechanics analysis.



# Transient Life Prediction Theory - Power Law SCG

Reliability formula for  $k$  discrete time steps over  $Z$  cycles:

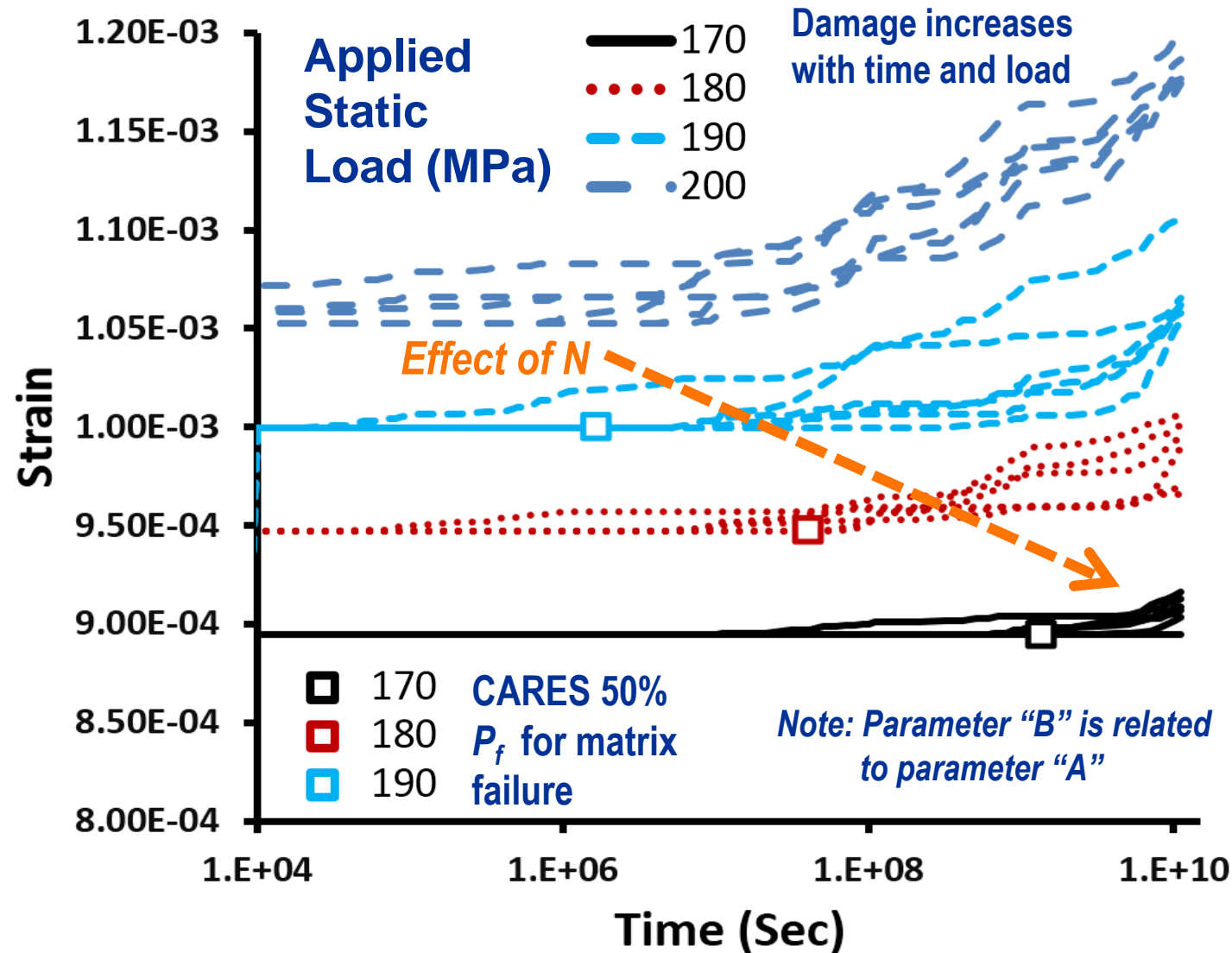
$$P_{SV}(t_k) = \exp\left\{-\sum_{i=1}^n \frac{V_i}{4\pi} \int_{\Omega} \left[ \dots \left[ \left( \frac{\sigma_{Ieq,k,Tmax}}{\sigma_{0BV,k}} \right)^{N_{V,k}-2} + \right. \right. \right. \\ \left. \left. \left. \frac{\sigma_{Ieq,k}^{N_{V,k}} Z \Delta t_k}{\sigma_{0BV,k}^{N_{V,k}-2} B_{V,k}} \frac{m_{V,k}(N_{V,j}-2)}{m_{V,j}(N_{V,k}-2)} + \frac{\sigma_{Ieq,j}^{N_{V,j}} Z \Delta t_j}{\sigma_{0BV,j}^{N_{V,j}-2} B_{V,j}} \frac{m_{V,j}(N_{V,i}-2)}{m_{V,i}(N_{V,j}-2)} + \dots \right. \right. \\ \left. \left. \dots + \frac{\sigma_{Ieq,2}^{N_{V,2}} Z \Delta t_2}{\sigma_{0BV,2}^{N_{V,2}-2} B_{V,2}} \frac{m_{V,2}(N_{V,1}-2)}{m_{V,1}(N_{V,2}-2)} + \frac{\sigma_{Ieq,1}^{N_{V,1}} Z \Delta t_1}{\sigma_{0BV,1}^{N_{V,1}-2} B_{V,1}} \frac{m_{V,1}}{m_{V,1}(N_{V,1}-2)} d\Omega \right]_i \right\}$$

- **Individual time step:** Each time step can have different loading, Weibull, and fatigue parameters. Compatibility of failure probability is maintained between the individual time steps

# Time-dependent Failure Example: Static Loading

(Matrix Damage Accumulation From Slow Crack Growth)

Strain response for applied static tensile load over time



**Service life prediction**

Longitudinal stress applied to a 0° SiC/RBSN ply

10 time increments per time magnitude

Slow Crack Growth Power Law:

$$\frac{da}{dt} = AK_{Ieq}^N$$

Weibull Parameters

$m = 7$  (Weibull slope)

$\sigma_0 = 106 \text{ MPa} \cdot \text{mm}^{3/7}$

Fatigue Parameters

$N = 20$  (fatigue slope)

$B = 1.0E9 \text{ MPa}^2 \cdot \text{sec}$

# MAC/GMC Methodology: Generalized Method of Cells (GMC) & High-Fidelity Generalized Method of Cells (HFGMC)

❖ *Micromechanics links the size scales & provides the composite response based on the composite constituent materials*

■ **FEAMAC:** MAC/GMC embedded in FEA as constitutive material

## GMC (1990s)

- 1<sup>st</sup> order displacement field in subcells
- Stresses and strains piecewise constant
- Number of linear algebraic equations function of number of subcells
- Local inelasticity/damage
- *No shear coupling*
- No “subcell mesh” sensitivity

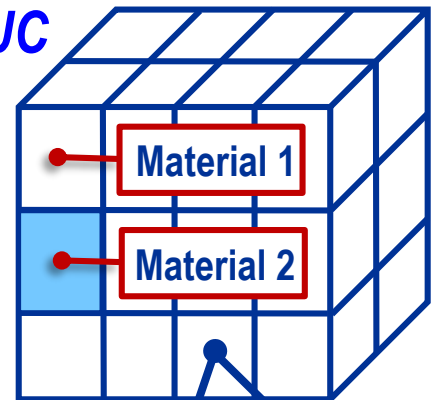
## HFGMC (2000s)

- 2<sup>nd</sup> order displacement field in subcells
- Elastic stresses and strains piecewise linear
- Number of linear algebraic equations is rather large
- Local inelasticity/damage
- *Has shear coupling*
- Has “subcell mesh” sensitivity

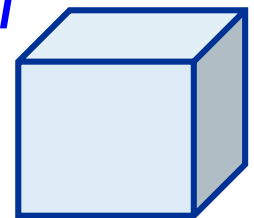
**Repeating Unit Cell (RUC)**  
of composite material

- ❖ RUC made subcells
- ❖ Multiscale capability

**RUC**



**Subcell**



**We currently only use GMC in FEAMAC/CARES**

Aboudi, J.; Arnold, S.M.; and Bednarczyk, B.A. (2013) *Micromechanics of Composite Materials: A Generalized Multiscale Analysis Approach*, Elsevier, Oxford, UK.

Aboudi, J.; Pindera, M.J.; and Arnold, S.M. (2003): Higher-Order Theory for Periodic Multiphase Materials With Inelastic Phases. *Int. J. Plast.*, vol. 19, pp. 805–847.

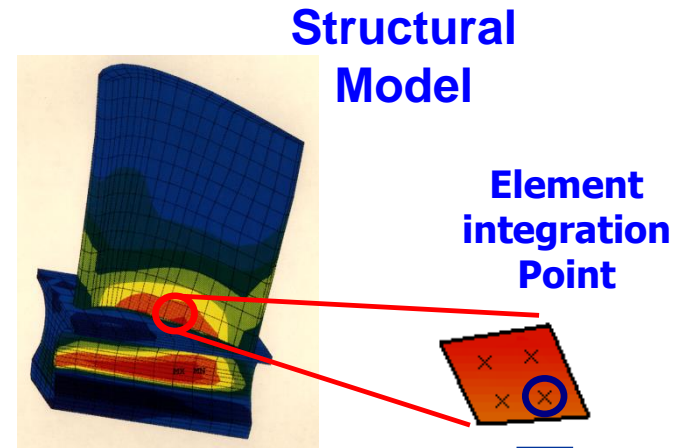
# CARES: Ceramics Analysys and Reliability Evaluation of Structures

## Life Prediction & Component Design Code For Advanced Ceramics

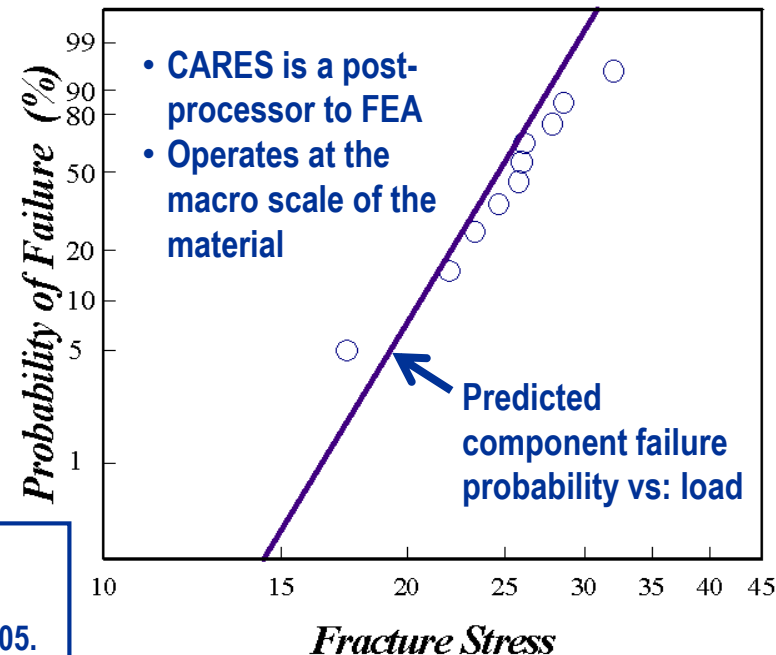
- Developed to predict the probability of failure of ceramic components under complex thermomechanical loading
- Combines Weibull & Weakest Link theory with concepts of linear elastic fracture mechanics (the *Batdorf Unit Sphere* model)

## Component Reliability Analysis Capability:

- Transient loads and temperatures
- Fast-Fracture Rupture
- Time-dependent ( $da/dt$ ) crack growth
- Cycle-dependent ( $da/dn$ ) crack growth
- Multiaxial stress failure models  
(*PIA* & *Unit Sphere* & *Tsai-Wu* & *Tsai-Hill*)
- Proof test



(CARES)  
reliability analysis



Nemeth, Jadaan, Gyekenyesi.: "Lifetime Reliability Prediction of Ceramic Structures Under Transient Thermomechanical Loads." NASA/TP-2005-212505, 2005.

# CARES: Life Prediction & Component Design Tools For Advanced Ceramics

Software (Ceramics Analysis and Reliability Evaluation of Structures)

*Predicts the probability of failure of ceramic components under load*

- Silicon nitride, silicon carbide, alumina
- Ultra high temperature ceramics
- MEMS materials – silicon; SiC
- Glass

Utilized worldwide for life prediction of brittle material components.

- Aerospace
- Automotive
- Electronic
- Energy
- Glass
- Medical
- Power

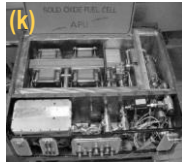
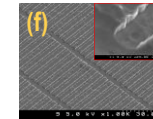


- NASA Software of the Year Award
- R&D 100 Award
- Federal Laboratory Consortium Technology Transfer Award
- American Ceramic Society Corporate Technical Achievement Award
- Enterprise Development, Inc. Innovation Award
- NASA Steven Szabo Engineering Excellence Award

## Applications

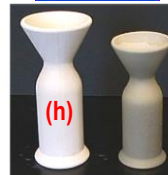
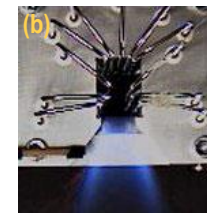
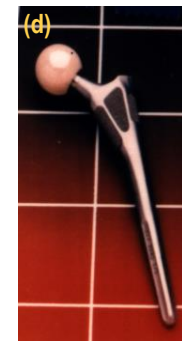
### MEMS

- Microturbine (a)
- Microrocket (b)
- Pressure sensor (c)



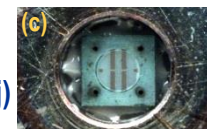
### Biomedical

- Hip joint (d)
- Dental Bridge (e)
- MEMS implants (f)



### Aerospace

- Turbine blade (g)
- Rocket Nozzle (h)
- Mars Aeroshell (i)



### Fuel Cell (SOFC)

- Power generation (j)
- Propulsion (k)

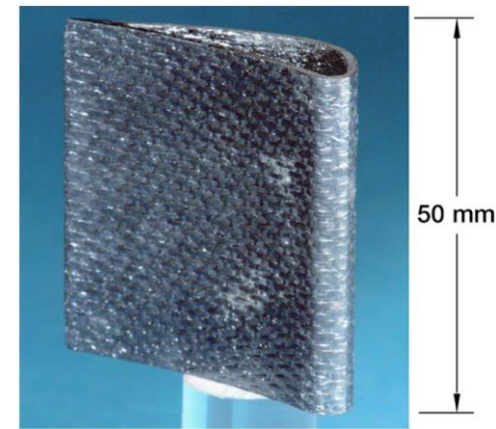
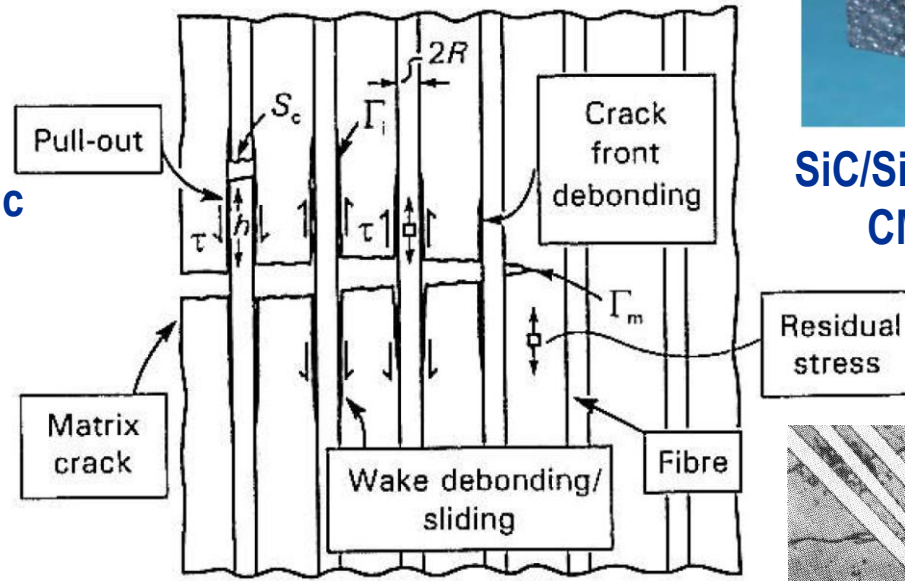




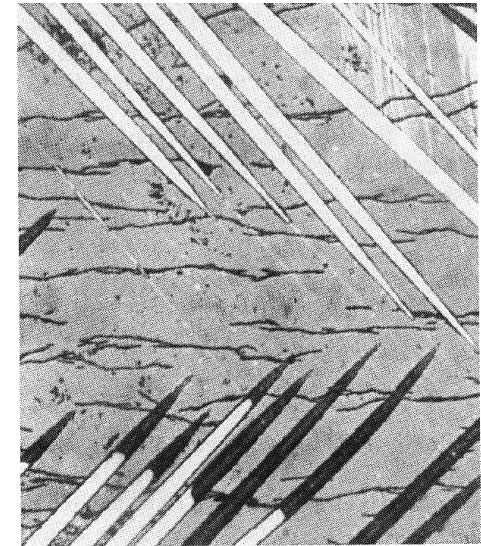
# Ceramic Matrix Composites (CMCs)

- Ceramic matrix composites (CMC) are being developed for hot section of advanced turbine engines (2700° F) and other uses.
- Specific mechanisms governing response of ceramic matrix composites need to account for in analysis approach:
  - Brittle material response
  - Weak, compliant interface
  - Residual stresses present due to processing
- Robust, efficient analysis tools required to analyze deformation, failure and life of these materials.

## Failure mechanisms



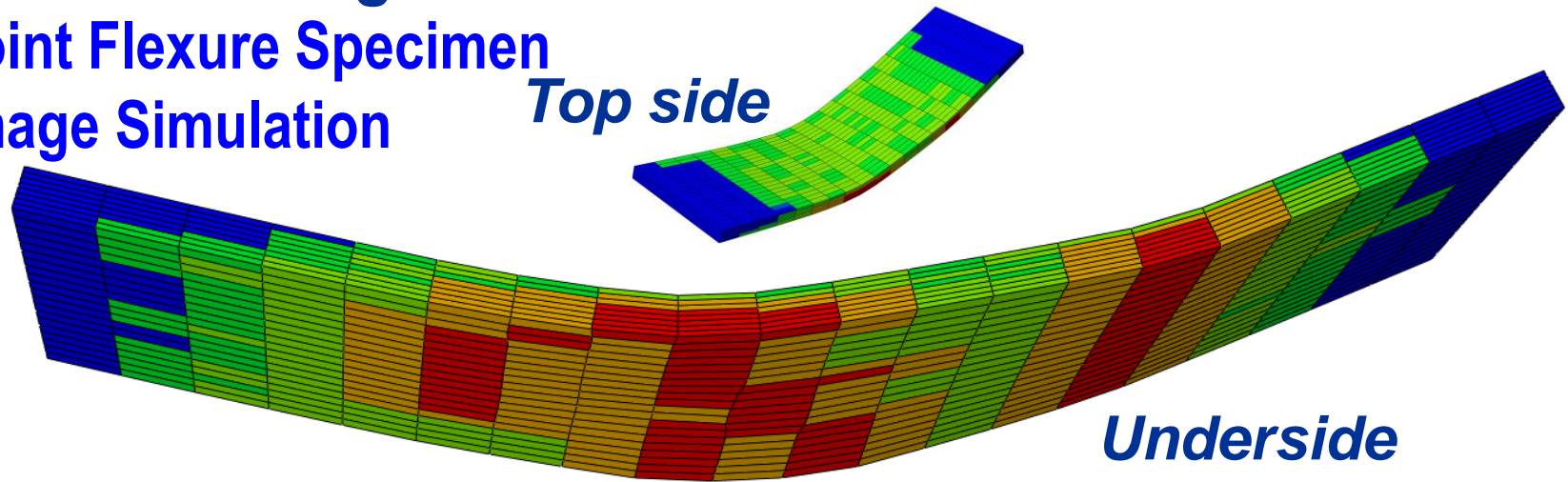
SiC/SiC (silicon carbide)  
CMC stator vane



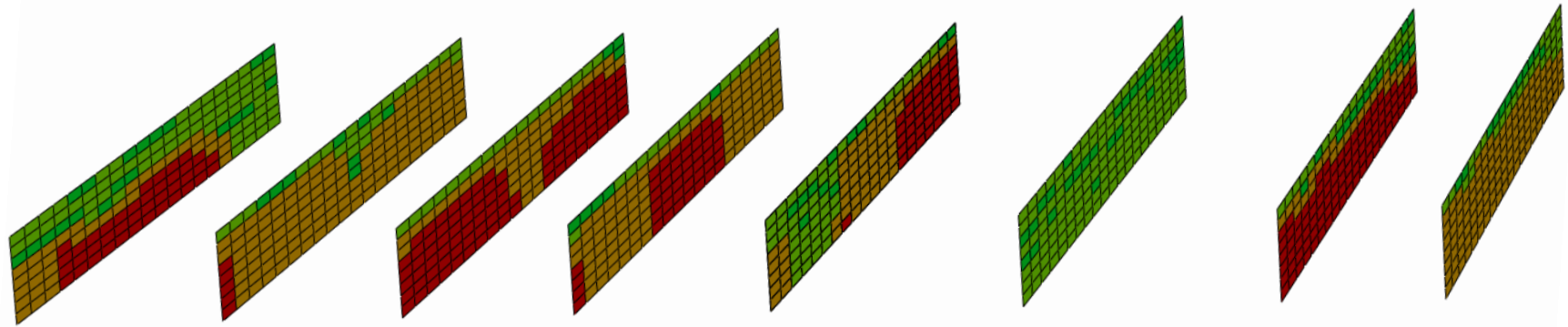
→ CMCs are designed to have “graceful failure”  
(non-linear stress-strain response) as opposed to brittle failure

# Work in Progress: Weibull Size Effect Demo

## 4-Point Flexure Specimen Damage Simulation



## Cut-view of damage at various points along the specimen length



*Initial effort intended for  
Weibull size effect demo  
of 3-point flexure, 4-point  
flexure, and tensile specimen*